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“Ryukyu Limestone” of Okinawa-jima, South Japan

—A Stratigraphical and Sedimentological Study—

By

Katsumi TAKAYASU

(Text and Plates)

Abstract

The “Ryukyu Limestone”, the host of the Quaternary geology of the Ryukyu Islands, is divided fundamentally into the main limestones and the accessory limestones. This division is based on the differences in lithological characters, fossil assemblages, distribution and thickness of beds, age of sedimentation, etc. The main limestones composing the major part of the “Ryukyu Limestone” constitute the Ryukyu Group together with the contemporaneous noncalcareous deposits, and they are the basement of the accessory limestones.

The Ryukyu Group is divided stratigraphically into two formations; the Lower and the Upper. The Lower Formation is the sediments which accumulated in the basins of the tectonic origin or in the valleys of the eroded basement and is represented by various lithofacies. On the other hand, the Upper Formation is more widely distributed than the Lower Formation, and its stratigraphical sequence of the lithofacies is rather constant everywhere. The Upper Formation is subdivided into the A, B and C Members based on characteristic fossil assemblages. Within these Members, the A Member is represented by some foraminiferal and molluscan fossils showing deeper water than a coral reef environment. Furthermore, the *Cyclolypeus-Operculina* bed of this Member, being fairly continuous, is a good horizon marker for the correlation of the Ryukyu Group not only in Okinawa-jima but also other islands. The biolithite facies, though poor in the Ryukyu Group as a whole, is recognized in the C Member of the Upper Formation and a part of the Lower Formation.

In order to analyse the sedimentary environments of the Ryukyu Group, the petrography and the fossil analysis under the optical microscope were made in connection to the field observation. As a result, the sedimentary environments of the Ryukyu Group can be generally inferred to have been shifted from the land prevailing condition disqualified for coral reef formation to the favourable condition for reef building, though the process of reef forming of the latter was interrupted for a short time by the intervention of deep sea environment as represented by the A Member in the Upper Formation.

As for the age of the Ryukyu Group, it is regarded to be Early and early Middle Pleistocene from the paleontological and stratigraphical aspects. The geologic structure of the Ryukyu Group is composed of many tilting blocks brought in by faulting after the completion of sedimentation. These tectonic movements of the maximum stage brought about the original configuration of the present islands. Since then, to the fringing areas of these emerged blocks the accessory limestones represented by the Minatogawa Limestone Formation were attached. However, it is also evident that mainly the tectonic movements affected the mode of the Ryukyu Group sedimentation such as local unconformities between the Lower and the Upper Formation and accelerated the change to shallow water of the sedimentary environment.

Therefore, the Ryukyu Group is the product of transgression due to tectonism, especially shown in the later stage. Contrasting with the main limestone deposition, the accessory limestones were the deposits formed under the influence of the eustatic sea level changes.

Lastly, the Quaternary geohistory of the Ryukyu Islands is reviewed from the viewpoint of the "Ryukyu limestone" stratigraphy.

I. Introduction

One of the most peculiar features in the geology of the Ryukyu Islands is the wide distribution of the Quaternary limestone, collectively called the "Ryukyu Limestone". The name "Ryukyu Limestone", originally spelled *Riukiu* Limestone, was first proposed by YABE and HANZAWA (1930) with regard to distinctions among raised coral reefs. Thereafter, by a series of works, especially by the paper of 1935, HANZAWA was highly esteemed for carrying out a detailed description of the geology of the Ryukyu Islands. Owing to HANZAWA's works, many researchers first recognized the significance of the "Ryukyu Limestone" in considering the geology of the Islands.

The studies on the "Ryukyu Limestone", however, together with the studies on the other geological formations, were forcibly interrupted for a long time by unfortunate circumstances in the Ryukyus such as the years of the Second World War and the succeeding occupation. After the War, with the remarkable progress of the geological sciences, several new interpretations and methods were rapidly introduced into the studies of the "Ryukyu Limestone" with in sufficient stratigraphical and sedimentological data.

During the time under occupation, the "Ryukyu Limestone" of Okinawa-jima was subdivided into three formations, that is, the Naha formation (the Naha limestone), the Yontan and the Machinato limestones ascendingly, and they were collectively called the Ryukyu Group in the reports on military geology by U.S. Army Forces and associated studies (FLINT *et al.*, 1959; MACNEIL, 1960). NAKAGAWA (1967; 1969a, b), who surveyed in Tokuno-shima and its neighbouring islands, Kagoshima Prefecture, applied the concept of sea level changes obtained from the studies at the Northeast Japan coast to the study of the Ryukyu Islands, and he regarded each formation of the Ryukyu Group as the terrace deposits which are correlated with each other by the altitude of their distribution. In this sense, the studies of HIRATA (1956, 1958) and YAMAZATO (1959, 1960) are similar to NAKAGAWA's work. They also divided the "Ryukyu Limestone" on the basis of the altitude of the distribution, and tried to compare the topographical and the ecological characters of the living coral reefs with those of the "fossil reefs". Further, KONISHI and his colleagues (KONISHI *et al.*, 1967; KONISHI *et al.*, 1970; KONISHI *et al.*, 1974) applied for the first time the radiometry of Th^{230} and Pa^{231} growth methods for the dating of the "Ryukyu Limestone", and they insisted in the explanation that neotectonism is a more effective gauge than eustatic sea level changes. They stated little about the stratigraphy and sedimentology of the limestones, but it seems that they subscribe to TOKUNAGA's opinion (1901), the limestones of the Ryukyu Islands are composite of raised coral reefs.

It is also true that several researchers have the opinion that the sedimentary

environment of the "Ryukyu Limestone" was not always so shallow as the coral reefs environment; HANZAWA (1948) already pointed out from the viewpoint of the study on larger foraminifers that sedimentation underwent at the depth of not shallow but of moderate.

Since the retrocession of "Okinawa" in 1972, many Japanese geologists have much interest in the study of the "Ryukyu Limestone", and a lot of information has been accumulated. YAZAKI (1976) and OYAMA (1976) reported the presence of deep sea molluscan fossils from the "Ryukyu Limestone" of Miyako-jima. Furthermore, the OKINAWA QUATERNARY RESEARCH GROUP (1976) clarified that most of the "Ryukyu Limestone" has nothing to do with the terrace deposits, though only a few limestones younger than the Middle terrace can be the object of the topographical correlation. Putting a heavy emphasis on this point, the writer stated in his paper dealing with the Quaternary limestones of the Motobu Peninsula, Okinawa-jima (TAKAYASU, 1976a), that the name of the Ryukyu Group should be used for the main part of the "Ryukyu Limestone" and the sediments of their contemporaneous facies other than younger terrace limestone. OKIMURA (1976) summarized his work on the Quaternary geology of Yoron-jima, Kagoshima Prefecture, in the same manner as the writer's proposal.

On the age of the main part of the Ryukyu Group or the "Ryukyu Limestone", there are divergences of opinion; some geologists regard it as the Middle and Late Pleistocene terrace deposits or the raised coral reefs, while others regard it as the Pliocene or the Early to Middle Pleistocene basement rocks.

In such circumstances, it was requested at first to establish an accurate stratigraphy of the "Ryukyu Limestone" as far as possible and to criticize those various opinions concerning the "Ryukyu Limestone". The writer started his work as a member of the Okinawa Quaternary Research Group in 1973, and surveyed the "Ryukyu Limestone" of about twenty islands in Okinawa Prefecture. An outline of the results obtained by the Research Group and the writer has been reported in several articles (OKINAWA QUATERNARY RESEARCH GROUP, 1976; KIZAKI and TAKAYASU, 1976; OKIMURA and TAKAYASU, 1976; TAKAYASU, 1976a, b). In this paper, the writer gives more detailed stratigraphical and sedimentological considerations on the "Ryukyu Limestone", with special reference to the Ryukyu Group of Okinawa-jima. The Quaternary geohistory of the Ryukyu Islands is briefly discussed from the viewpoint of the "Ryukyu Limestone".

II. Geologic Outline of Okinawa-jima

A. Topography

Okinawa-jima, the largest islands of the Ryukyu Islands, is located at the middle of the Islands which extend from 31°N lat. to 24°N lat. (Fig. 1). From the viewpoint of geography, this island is divided into several units as shown in Fig. 2.

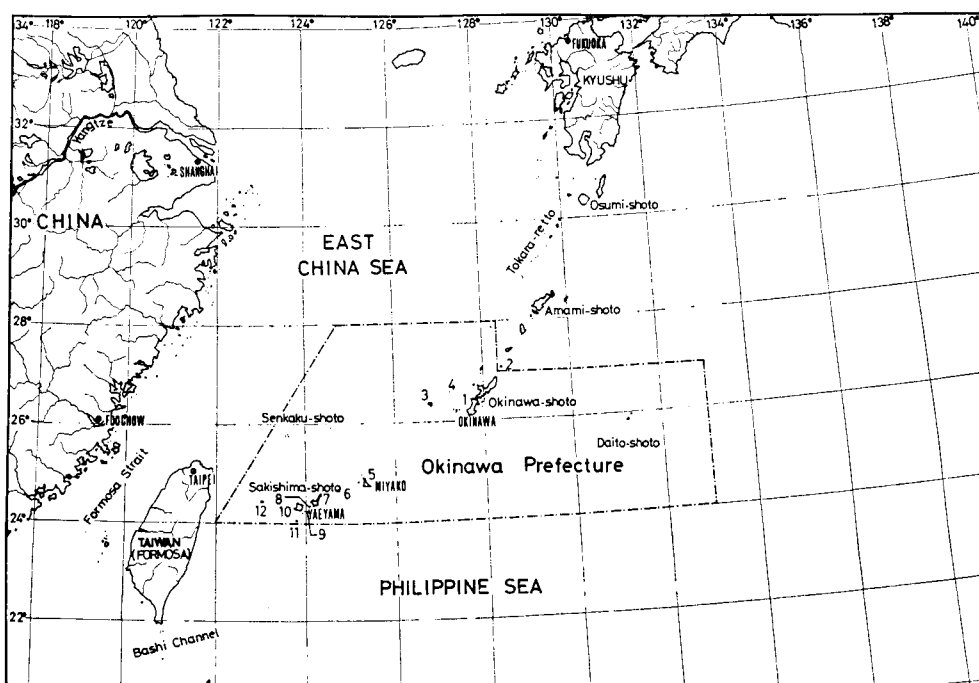


Fig. 1. Map showing location of the Ryukyu Islands. The Islands are divided geographically into three parts; the Northern Ryukyus (Osumi-shoto), the Central Ryukyus (Amami- and Okinawa-shoto) and the Southern Ryukyus (Sakishima-shoto consisting of Miyako- and Yaeyama-shoto). The numbers in the map are index for Table 4 in Chapter III; 1. Okinawa-jima, 2. Yoron-jima, 3. Kume-jima, 4. Aguni-jima, 5. Miyako-jima, 6. Tarama-jima, 7. Ishigaki-jima, 8. Taketomi-jima, 9. Kohama-jima, 10. Iriomote-jima, 11. Hateruma-jima, 12. Yonaguni-jima. (shoto; islands, jima; island)

The topographical divisions of Okinawa-jima are summarized as shown in Table 1. Among these topographical divisions, the terraces are classified into the Higher, the Middle and the Lower in accordance with their surface altitudes. The Higher terraces are distributed in Kunigami and Motobu areas, Northern Okinawa, and usually covered by so called "Kunigami gravels". HANZAWA (1935) considered that gravels as the deposits overlying the "Ryukyu Limestone", but his "Kunigami gravels" is known as the collective name for gravel deposits of various stages (NAKAGAWA, 1969b; TAKAYASU, 1976b).

It is conspicuous that the height of the surfaces lower than of the Middle terrace of the Minatogawa Plane are rather constant without any local variation. This is characteristic of the terrace topography throughout Okinawa-jima as well as in other islands.

In addition, it is unique in Okinawa-jima that the land form of the "Ryukyu

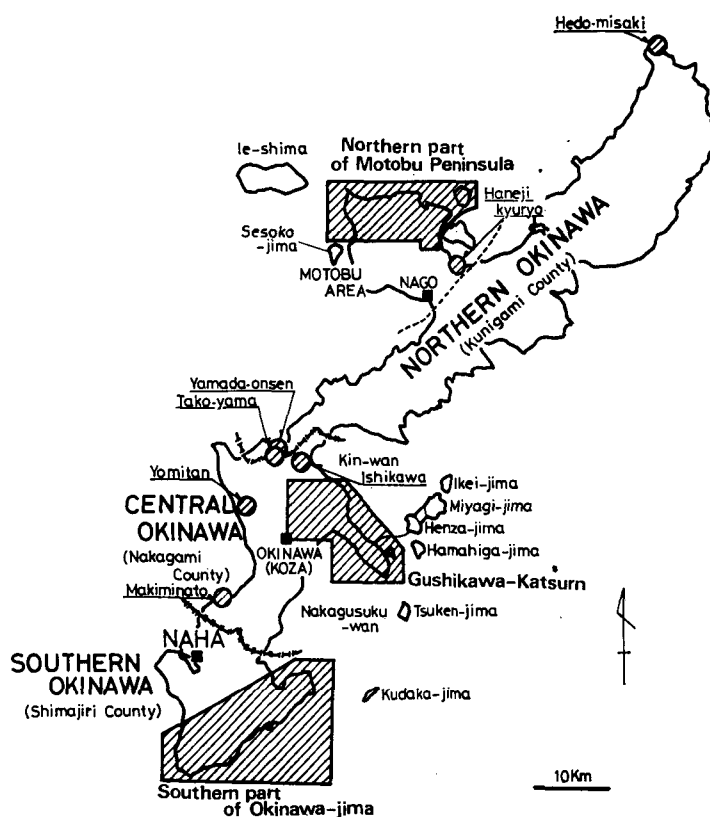


Fig. 2. Index map of Okinawa-jima showing location of study areas.

Limestone" is represented by mesa and cuesta topographies in southern part (Pl. 14, Fig. 1), and butte in central part. It may be due to the effect of lithologic or tectonic control otherwise. Furthermore, the limestone walls observed everywhere along cliffs are considered to be case hardening of exposed limestone beds (FLINT *et al.*, 1953).

B. Geology

The basement rocks of the "Ryukyu Limestone" are composed of various sedimentary rocks and small intrusive rocks ranging from Permian to Neogene (Fig. 3). They are arranged zonally and divided structurally from inner (continental side) to outer (oceanic side), the Motobu belt (Permian and Triassic), the Kunigami belt (Jurassic?–Eocene) and the Shimajiri belt (Neogene) respectively (KONISHI, 1965).

Among them, the Shimajiri Group of the Shimajiri belt is the most important deposit in relation to the "Ryukyu Limestone". It is more than 2,000 m in total thickness, and is composed of thick siltstone with intercalations of sandstone and tuff (FUKUTA *et al.*, 1971). According to the studies of planktonic foraminifers and calcare-

Table 1. Classification of landforms of Okinawa-jima

Topographic division		Type area	Altitude	Geology
Mountain land		Northern Okinawa (Kunigami, Motobu)	496 m (Yonaha-dake) 453 m (Yae-dake)	Pre-Neogene basement rocks
Hill land		Central and Southern Okinawa	Less than 100m	Shimajiri Group
Limestone landforms (mesa, cuesta, butte)		Central and Southern Okinawa	The highest point is 198 m	Ryukyu Group (the main part of the "Ryukyu Limestone")
Terrace	Higher	Northern Okinawa (Kunigami, Motobu)	80-200 m	"Kunigami gravels"
	Middle	Coastal area	40-60 m 20-30 m (Minatogawa Plane)	Gravels and the accessory part of the "Ryukyu Limestone"
	Lower		10-15 m 5-7 m	
	Coastal landforms (bench, dune, reef, mangrove swamp)		Less than 5 m	Postglacial raised coral reef limestone, calcareous beach deposits, alluvial clay, etc.

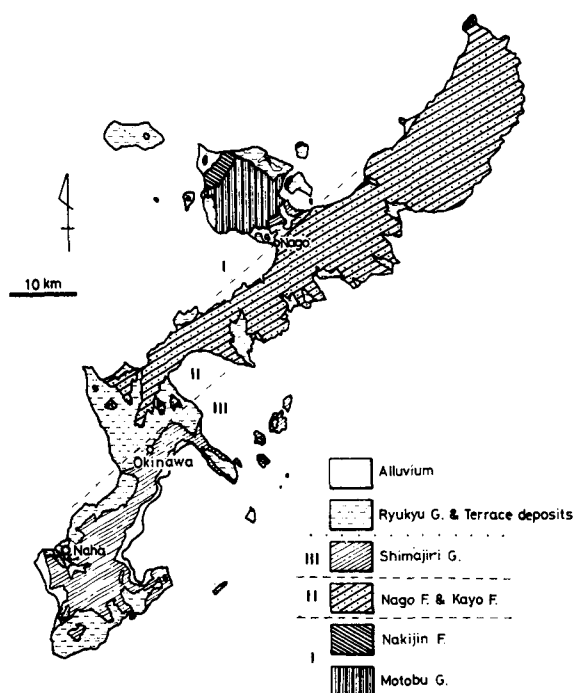
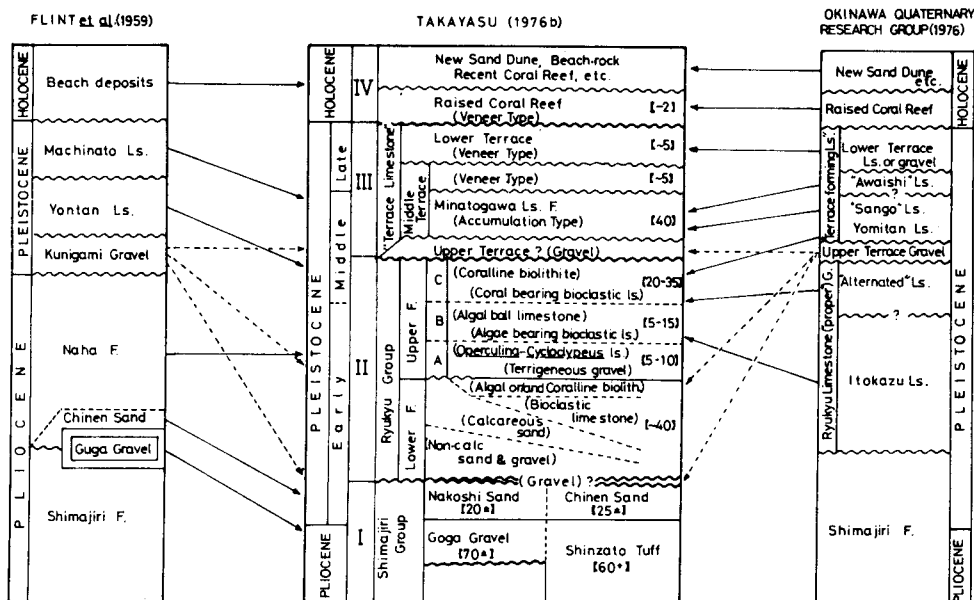


Fig. 3. Geologic outline of Okinawa-jima. I; Motobu belt (the Motobu Group, Permian, and the Nakijin Formation, Trias), II; Kunigami belt (the Nago and the Kayo Formations, Jurassic?-Eocene), III; Shimajiri belt (the Shimajiri Group, Neogene). The name of each belt is based on KONISHI (1965).

Table 2. Stratigraphic sequence of the Quaternary System of Okinawa-jima (Takayasu, 1976b)



ous nannoplanktons, the Shimajiri Group is regarded as the sediments of the Late Miocene to Early Pleistocene (NATORI *et al.*, 1972; NISHIDA, 1973; IBARAKI and TSUCHI, 1976; NATORI, 1976).

As the result of geological re-examination (TAKAYASU, 1976b), the Quaternary System of Okinawa-jima was summarized as in Table 2.

III. Stratigraphical Study of the "Ryukyu Limestone"

A. General Stratigraphy

1. Fundamental division of the "Ryukyu Limestone"

The writer proposed tentatively to divide the "Ryukyu Limestone" into the Ryukyu Group and the "terrace limestones" (TAKAYASU, 1976a, b). Though this concept is still valid, the terminology of "terrace" seems to cause confusion in the definition. Therefore, in this paper the writer adopts the new term of *accessory limestones*, i.e. the accessory part of the "Ryukyu Limestone", instead of the "terrace limestones". The Minatogawa Limestone distributed in Southern Okinawa is a representative of the accessory limestones in Okinawa-jima. The limestones of the Ryukyu Group are called the *main limestones*, i.e. the main part of the "Ryukyu Limestone" excluding the accessory limestones. The reason why the "Ryukyu Limestone" should be divided into two parts would be understandable in Table 3.

Table 3. Comparison between the main limestones and the accessory limestones

	Main limestones	Accessory limestones
Distribution	widely (overlapping whole area of the Shimajiri Group and also moderate area of the pre-Neogene basements).	limited (accessory distribution at the circumference of each island).
Thickness	about 100 m or more.	less than 40 m.
Lithology	bioclastic limestone for the most part and biolithite in part. micrite matrix rich.	biolithite rather predominant. sparry calcite cement rich.
Fossils	including some fossils showing not such shallow water as the coral reef can be formed.	representatives at shallow environment similar to the littoral zone around present islands.
Identity of stratigraphy	fairly continuous laterally in accordance with the more upper horizon.	not clear as its limited distribution.
Preservation of depositional surface	extremely poor	clear as the terrace topography
Structure	faulted and tilted. more than 20° in dip near fault.	scarcely disturbed by tectonic movements.

Besides, following the definition of YABE and HANZAWA (1930), the name of "Ryukyu Limestone" is adopted for collective use to the Pleistocene limestones* excluding Postglacial raised coral reef limestone.

2. The Ryukyu Group—the main limestones and their contemporaneous sediments

In consideration of the lithofacies and the fossil assemblages, the Ryukyu Group is divided stratigraphically into two formation units, the Lower and the Upper. Furthermore, the Upper Formation is subdivided by the characteristic fossil assemblages into three members of the A, B and C ascendingly (TAKAYASU, 1976a, b). The Lower Formation is the sediment which accumulated in the tectonic basins or in the valleys of the eroded basements. Therefore, the thickness of the Formation varies from place to place. The lithofacies of the Lower Formation also vary from noncalcareous to calcareous facies according to the basement topography and the quantity of the terrigenous fragments. But, in general, it becomes more calcareous towards the upper part and at the top the coralline and/or algal biolithite facies are observed distinctly.

The Upper Formation overlies the Lower Formation conformably, and is distributed more widely than the Lower Formation. The unconformity between the basement and the Upper Formation is rather smooth as compared with the relation between the Lower Formation and the basement. From the evidence of overlapping, it is clear that the depositional area of the Upper Formation spreaded out successively. Therefore, the lateral facies change is not conspicuous in comparison with the Lower

* Though HANZAWA (1935) considered the age of the "Ryukyu Limestone" to be the Pliocene to Early Pleistocene, the present researchers regard it as the Pleistocene based on the relation to the Shimajiri Group.

Formation.

In the lowest part of the Upper Formation, the *Cycloclypeus-Operculina* beds in the limestone facies are fairly continuous laterally, and form a good horizon marker. The *Operculina* bed occupies a position slightly lower than the *Cycloclypeus* bed generally, but sometimes either one is missing.

Cycloclypeus assemblage is dominated by *C. carpenteri*. According to HANZAWA (1948), this larger foraminifera is usually known at the depth of about 100 m in the present sea bottom, and some other larger foraminifers accompanied with it are also inhabitants of the moderate depth. Therefore, he considered that the "Ryukyu Limestone" was deposited at deeper environment than the depth of coral reef formation. In addition to this, a bivalve, *Plicatula mulicata*, is sometimes found at a horizon immediately above the *Cycloclypeus* bed. This bivalve is also present in the "Ryukyu Limestone" of Miyako-jima. The molluscan assemblages of the *Plicatula* horizon are represented by shells which are considered to be indicative of the depth between 60 and 100 m (OYAMA, 1976).

From the facts mentioned above, the *Cycloclypeus* bed and its associated horizons are significant to consider the sedimentary environment of the Ryukyu Group.

The writer called the beds of *Operculina* and *Cycloclypeus* the A Member. In the lower half of the A Member are often some terrigenous fragments, and in a part of the *Operculina* swarm, generally about two meters in thickness, are sometimes intercalated one or two thin layers of the terrigenous reddish brown clay.

The A Member is overlain by the B Member which is characterized by the presence of algal limestone. The algae appears to be ball-like in many cases, but sometimes is broken into fine fragments *in situ*. In the B Member, the number of fossil species increases upward, while the content of terrigenous fragments decreases more and more. The C Member covers the B Member, and is represented by coralline bioclastic limestones. In some areas it changes laterally into coralline biolithites.

3. The Minatogawa Limestone Formation—as a representative of the accessory limestones

The Minatogawa Limestone corresponds roughly to the Machinato limestone of FLINT *et al.* (1959). But now, the topographical situation of type locality of the latter has been strongly changed artificially and moreover is hard to access owing to the military establishments. Therefore, the writer made the re-definition of that limestone formation in Minatogawa, Southern Okinawa, and requests to shift the type locality (TAKAYASU, 1976b).

The Minatogawa Limestone Formation filled low relief on the erosion surface of both the Ryukyu Group and Shimajiri Group with remarkable unconformities. The Formation is divided lithologically into the Lower and the Upper Members. The Lower Member represented by coralline biolithites usually contains the huge limestone blocks of the Ryukyu Group. The Upper Member conformably overlying the Lower

Member is represented by foraminiferal calcarenite or calcirudite with many rounded intraclasts.

The distribution of the Minatogawa Limestone is followed up to about 30 m above sea level continuously, and forms the Minatogawa Plane of 20–30 m in height. Besides, it must be mentioned that even at some places of 55–60 m in height, other limestones which look like the Upper Member of the Minatogawa Formation distributed in a small amount near the distribution area of the Minatogawa Limestone Formation. The relation between those two limestones is not yet clarified.

As for other accessory limestones, the small distributions of coralline biolithite and/or algal ball limestones are observed on the Lower surfaces of 10–15 m and 5–7 m in height respectively. Their thickness is generally less than 5 m.

B. Local Stratigraphy of the Ryukyu Group

1. Northern part of Motobu Peninsula

The writer already reported on the Quaternary limestones of this area (TAKAYASU, 1976a), and the summary will be mentioned briefly in this article.

The lithofacies of the Lower Formation differs with each other between the eastern area (Nakijin Village area) and the western area (Motobu Town area) (Fig. 12a, in Chapter IV). In the eastern area, it is represented by calcareous sand beds called the Unten sand beds. The Unten sand beds become more calcareous westwardly. The lower Formation of the western area is stratified bioclastic limestones of the Urasaki limestone beds. It should be noted that the Urasaki limestone beds reveal sometimes remarkable cross bedding or lamination (Pl. 15, Fig. 5), with many terrigenous fragments in the lower part. The difference between the lithofacies of the eastern and the western areas may be explained as that of contemporaneous heterotopism due to the difference in sedimentary environments, but the calcareous sand of the Unten sand beds is recognized below the bioclastic facies of the Urasaki limestone beds at several localities. Therefore, the sedimentation of the Unten sand beds might have preceded that of the Urasaki limestone beds during the first stage of the deposition.

The Lower Formation abuts on the basement rocks, having fragments or boulders of basement rocks abundantly in the basal part. On the other hand, the Lower Formation of Kourijima, off Unten, Nakijin Village, is represented by the stratified bioclastic limestones with poor cross bedding, different from the Urasaki limestone beds.

As for the Upper Formation of this area, it is easy to distinguish among the three Members, A, B and C, especially in the eastern area. The *Operculina* bed of the A Member (Pl. 14, Fig. 4) has a good lateral continuity all over the Peninsula and also in Kourijima. In the western area of the Peninsula, the *Cycloclypeus* limestone lies directly above the *Operculina* swarm part. The B Member is slightly thicker in the eastern area than in the western area. Furthermore, in the western area it is often difficult to distinguish lithologically the B Member from the C Member. The C Member is represented by weakly layered bioclastic limestones (Pl. 15, Fig. 4), and the coralline biolithitic lime-

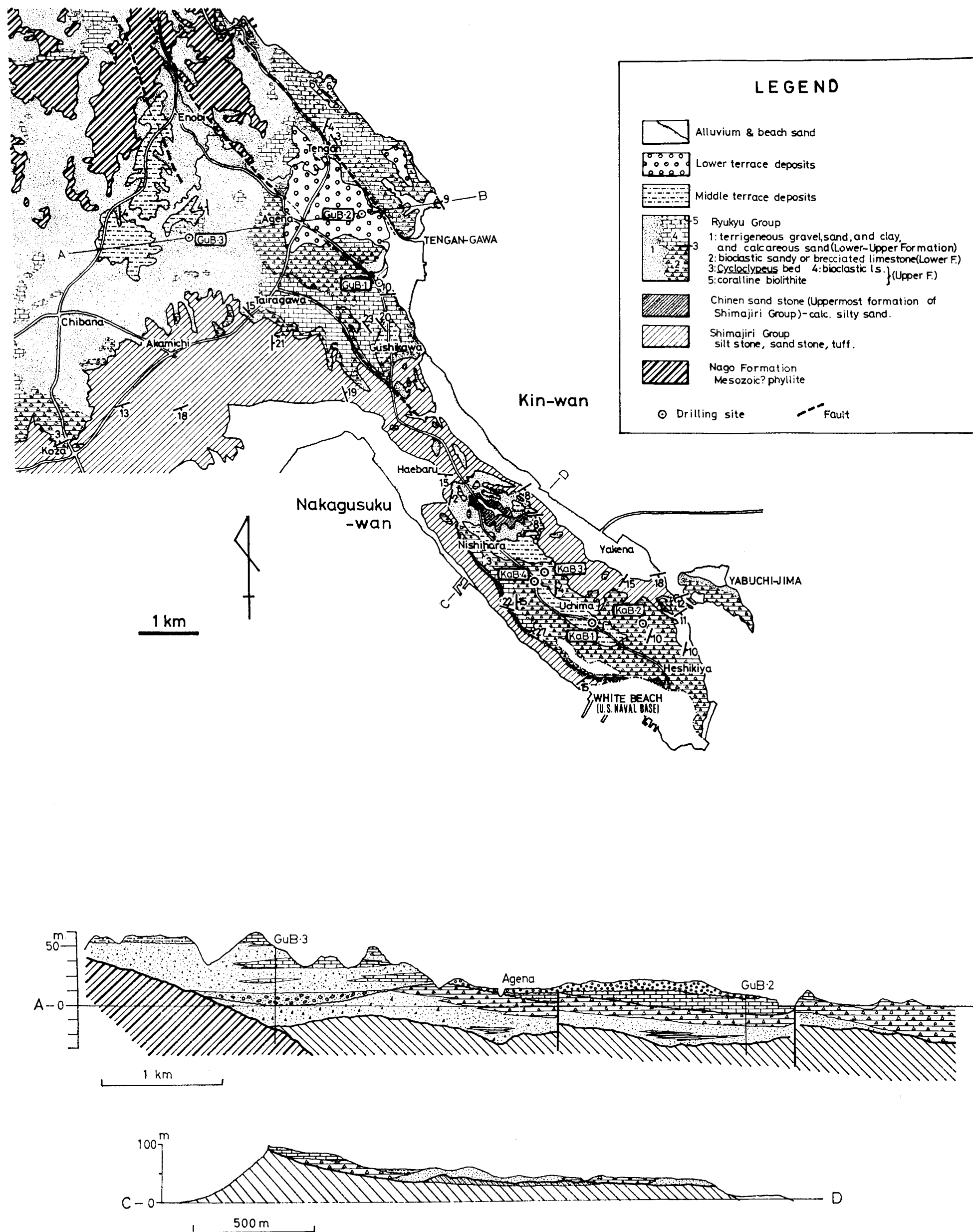


Fig. 4. Geologic map of Gushikawa-Katsuren area.

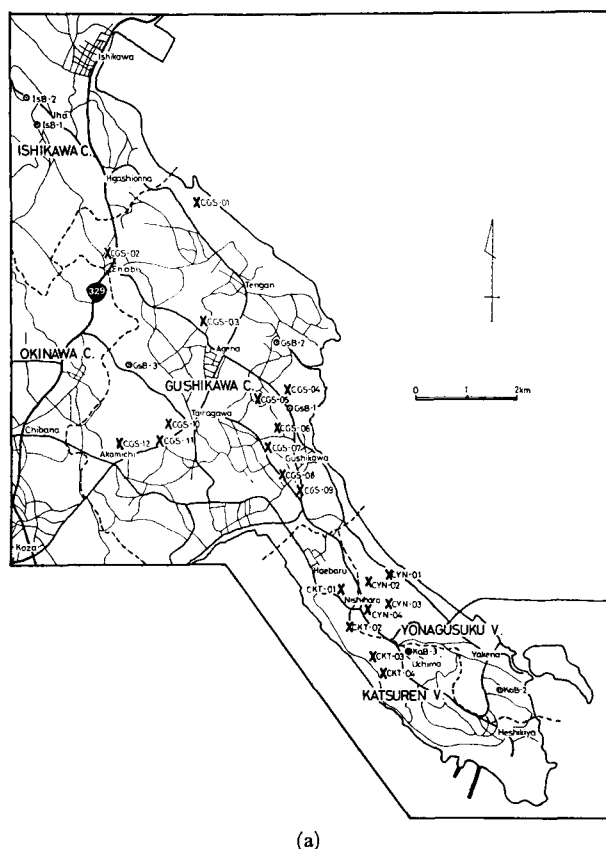
stones are also distributed sporadically around the salient part of the basement (Pl. 14, Fig. 3). Hitherto, these biolithitic limestones had been once regarded as a part of the "terrace limestones" of the upper surface of the Middle terraces (TAKAYASU, 1976a). However, after detailed surveys, the writer has come to conclusion that these biolithitic limestones are correlated with the coralline biolithitic limestones of the C Member, and both are contemporaneous. At several localities in the eastern area of the Peninsula, the biolithite of the C Member unconformably overlies the Unten sand beds.

2. Gushikawa-Katsuren area

This area is divided lithologically into three areas as follows; the western area (the western area of Gushikawa City) where the Lower and Upper Formations are both predominated by noncalcareous facies, the central area (the eastern area of Gushikawa City and the neck of Katsuren Peninsula) where the Lower Formation is dominant in the noncalcareous facies but the Upper Formation is characterized by the calcareous facies, and the eastern area (the largest part of Katsuren Peninsula) where both Formations are represented by calcareous facies (Fig. 4). The correlation between the three areas is not yet sufficiently confirmed because a good horizon marker is absent in the noncalcareous facies. In calcareous facies, however, the *Cycloclypeus* bed can be fairly well traced laterally.

The Lower Formation of the western area consists mainly of noncalcareous gravels or sands, and contains many molluscan shells and sometimes coralline fragments. The Upper Formation intercalates with the limestone pebble beds in the lower part. Though this information was obtained from a drilling core (GuB-3, in Fig. 5), it is possible to say that these limestone pebbles were derived from the limestones of the Lower Formation somewhere in the more eastern area. The calcareous parts increase upward in the Upper Formation, but most of the Upper Formation is occupied by noncalcareous sand and gravel facies. In the noncalcareous parts of the Upper Formation, the fossils are not yet reported. The calcareous parts are intercalated within the noncalcareous parts in large lenticular limestone bodies. These limestones remain as buttes which escaped erosion.

The Lower Formation of the central area reveals particularly complicate facies changes. From the drilling (GuB-1, in Fig. 5) near the estuary of the Tengan-gawa, dark greyish silt beds containing organic matter were found. In the silt beds, brackish water foraminifers represented by *Ammonia* were yielded. Similar silt beds were also found in the drilling cores of the Ishikawa City area (IsB-1 and IsB-2, in Fig. 5). Well sorted and weakly cross laminated noncalcareous sand beds which look like dune sand beds are distributed in the neck of Katsuren Peninsula (CGS-01, in Fig. 5), where the altitude of the basement Shimajiri Group is generally higher than in other areas. Towards the west, the sand beds change gradually into stratified sand beds intercalating thin silt layers (CGS-09, in Fig. 5), and towards the east they change to sand beds containing sporadic calcareous parts (CYN-01, in Fig. 5). Another variety of the Lower



(a)

Fig. 5. Columnar sections (right) and their localities in Gushikawa-Katsuren area (on legend see Fig. 6).

Formation in this area is represented by well stratified bioclastic limestones. The limestones are distributed in the northern area of Tairagawa and Gushikawa, Gushikawa City. They overlie the noncalcareous sand beds, a part of which shows cross bedding (Pl. 15, Fig. 6).

The Upper Formation of the central area is represented by stratified bioclastic limestones. Though the coralline biolithites correlative with the C Member are also distributed on the top of the ridge north of Tengan, in most of this area, it seems that only the B Member is distributed. In the neck of Katsuren Peninsula, all of the Upper Formation is absent. Additionally, near the neck of Katsuren Peninsula (CGS-09, in Fig. 5), the Upper Formation overlies the Lower Formation unconformably (Pl. 15, Fig. 3). Giving attention to these facts of distribution and local unconformity, the writer inferred that the Ryukyu Group of this area suffered the tectonic movements during the deposition, and the sedimentary basin was separated into the east and the

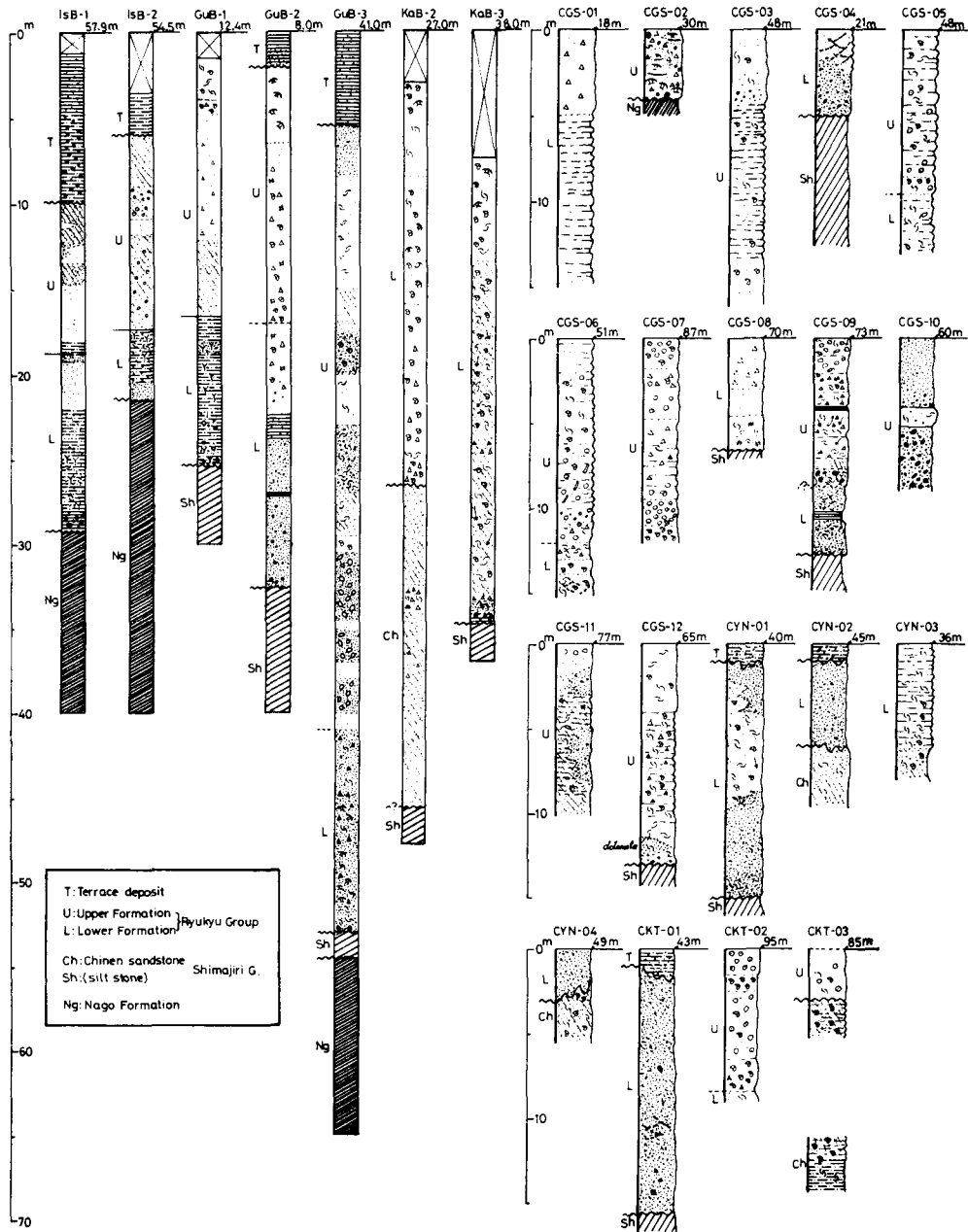


Fig. 5. (b)

west by uplift of the neck of Katsuren Peninsula (TAKAYASU, 1976b).

In the eastern area, it is known by the results of drillings (KaB-2 and KaB-4, in Fig. 5) that the thick Lower Formation is distributed under the axial part of the Peninsula. The lithofacies changes from the calcareous sand of the west to the clastic limestone of the east. At several outcrops, the clastic limestones show remarkable stratification and cross bedding. The Upper Formation of this area is distributed mainly along the southeastern edge of the Peninsula, and it overlies directly the Shimajiri Group in general. The sequence from the *Operculina-Cycloclypeus* limestone of the A Member to the algal ball limestone of the B Member can be observed at several outcrops (CKT-02, in Fig. 5), while the C Member is absent.

3. Southern part of Okinawa-jima

In this part, the Lower and Upper Formations are both represented by calcareous facies. As shown in Fig. 7, this part is divided on the basis of the difference in tectonism into the western area, west to the Minatogawa Limestone, and the eastern area of the opposite side. In the western area (mainly Itoman City area), tectonic movements were vigorous after the deposition of the Ryukyu Group, while in the eastern area (mainly the area of Chinen Peninsula) the erosion was more predominated than the tectonic

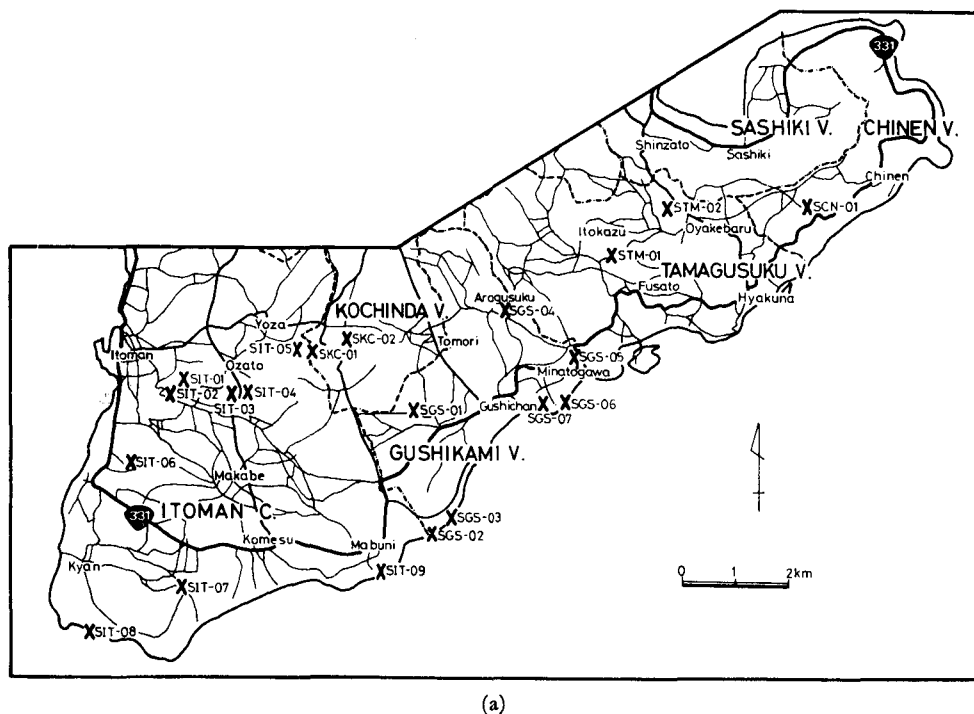


Fig. 6. Columnar sections (right) and their localities in the southern part of Okinawa-jima.

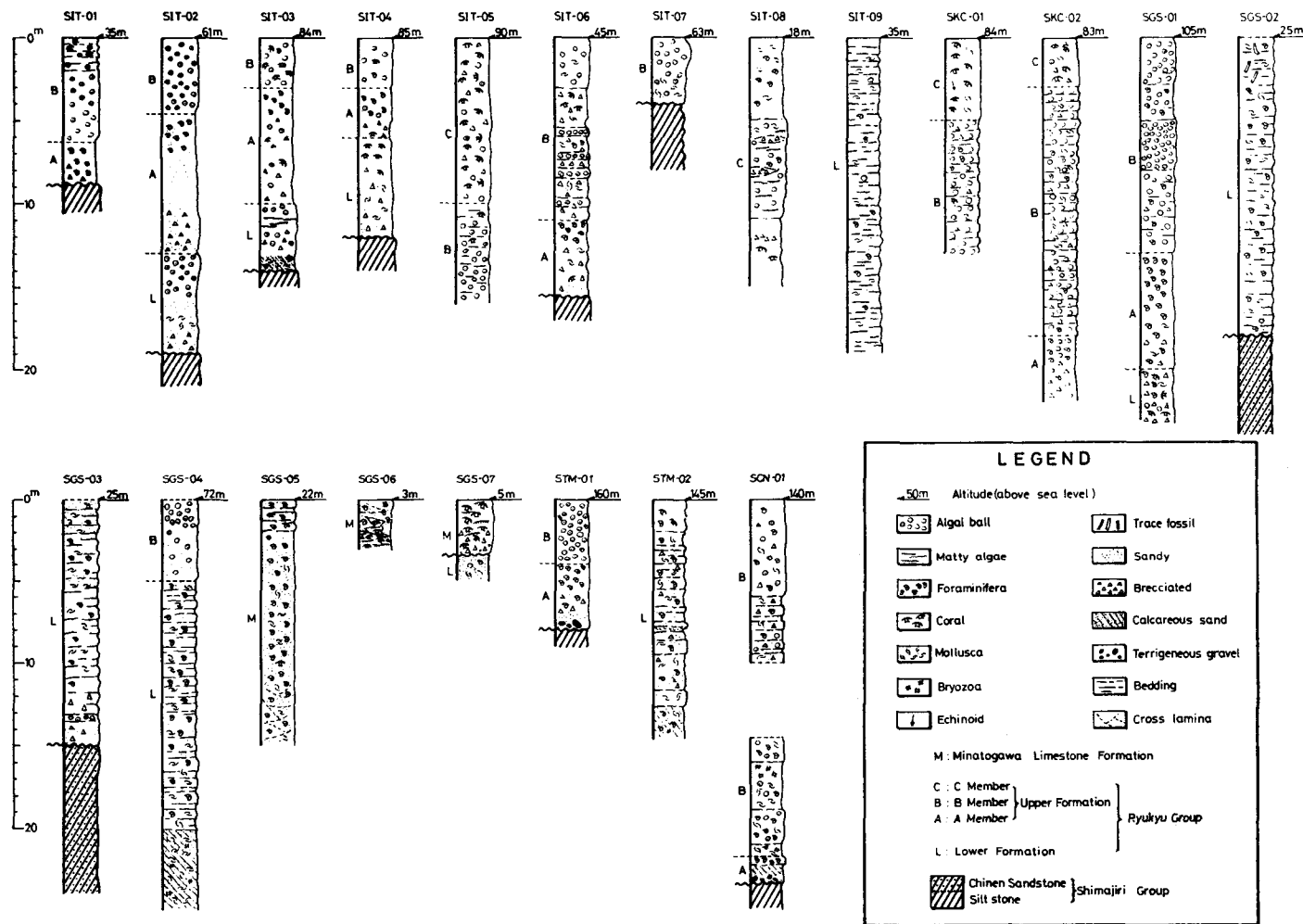


Fig. 6. (b)

control of topography.

The Lower Formation of the western area is limited in the eroded depressions on the Shimajiri Group, and in some basal horizons the presence of calcareous sand beds is recognized (SIT-03 and SGS-04, in Fig. 6). At the top of the Lower Formation, coralline or algal biolithites are sometimes recognized (SIT-03, in Fig. 6). The Upper Formation of the western area is divided into three Members lithologically. Among them, the algal ball limestone of the B Member (Pl. 14, Fig. 5) and coralline bioclastic limestone or coralline biolithite of the C Member are distinctive.

In the eastern area, the unconformity between the Shimajiri Group and the Ryukyu Group has a position up to more than 100 m above sea level. The bioclastic limestones of the Lower Formation are distributed in the neighborhood of Oyakebaru (STM-02, in Fig. 6), and the sequence from the *Cycloclypeus* limestone of the A Member (Pl. 14, Fig. 6, Pl. 16, Fig. 2) to the algal ball limestone of the B Member of the Upper Formation is observed at several outcrops around the plateau of Itokazu (SIT-01, in Fig. 6). The limestones correlative with the C Member are absent. The coralline limestones are observed in only a part of the top of the Lower Formation.

Furthermore, the Itokazu limestone and the "Alternated limestone" of the OKINAWA QUATERNARY RESEARCH GROUP (1976) are correlated respectively with the Upper Formation and with a part of the Lower Formation and the Upper Formation of the Ryukyu Group in the writer's stratigraphical definition.

4. Hedo-misaki

The limestones of the Ryukyu Group are distributed in a small area at Hedo-misaki cape. In this area the limestones cover the basement of the Triassic limestone of the basement and those include numerous granules of the latter. As for the fossils, algae which coat the granules in ball shape of less than 1 cm in diameter are abundant, and *Cycloclypeus* is common.

Hitherto, the limestones were correlated with the Machinato limestone, since the topography of this cape shows the flat plane of 20–30 m in height (FLINT *et al.*, 1959). From the lithological characteristics, however, those limestones may belong to the upper part of the A Member.

Besides, the limestone similar to the algal ball-*Cycloclypeus* limestone of Hedo-misaki is also recognized in Yoron-jima, about 20 km off the cape. OKIMURA (1976) correlated this limestone with the lowest horizon of the Middle Formation of the Ryukyu Group of his stratigraphical division.

5. Circumference of Haneji-naikai

In the neck of Motobu Peninsula, loose sand beds with gravels of about 30 m in thickness, are laid horizontally on the Goga gravel beds and Nakoshi sand beds which incline towards the southeast. Sand beds with gravels intertongue with the calcareous sand beds near Nakoshi. Calcareous sand beds with numerous granules and quartz grains are also distributed in O-jima and Yagachi-jima, northern partitions of Haneji-

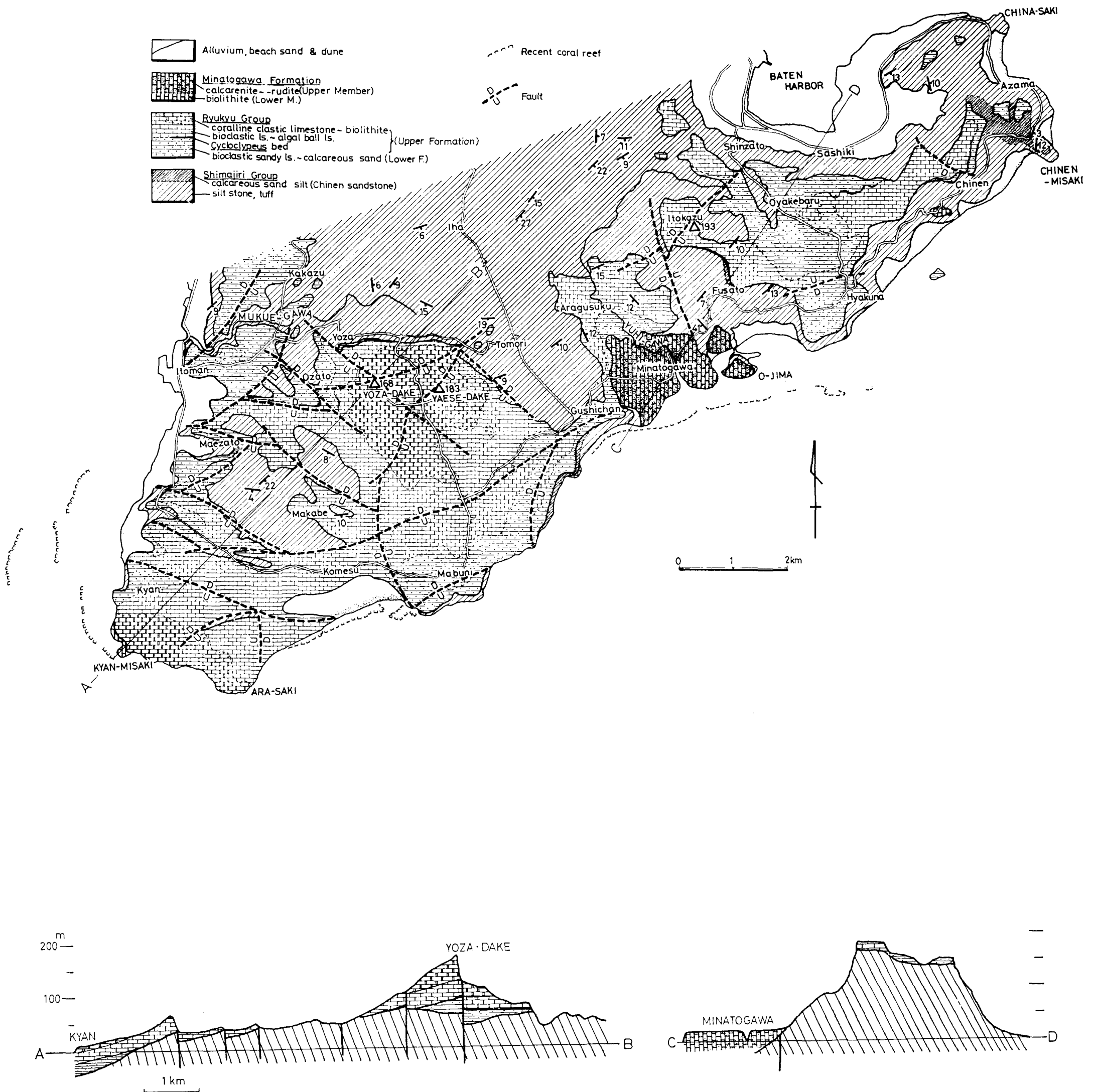


Fig. 7. Geologic map of the southern part of Okinawa-jima.

naikai. The calcareous sand beds of these islets are considered to be contemporaneous with the loose sand beds in the neck of Motobu Peninsula. *Operculina* swarm parts are found in these calcareous sand beds, while their lateral continuity has not been clarified. The calcareous sand beds of the western area of Yagachi-jima contain abundant remains of *Pecten* and they are lithologically similar to the Unten sand beds of the eastern area in Motobu Peninsula, which is the opposite coast with a narrow strait.

Most of the sediments in this area are probably correlated with the Lower Formation of the Ryukyu Group.

6. Yamada-onsen

The lowest part is represented by noncalcareous sand beds with a large amount of phyllite fragments of the Nago Formation. Fossils have not yet been found in these sand beds. The noncalcareous sand facies change promptly to calcareous sand facies and upwardly to bioclastic limestone (Fig. 8). In accordance with such lithological change, the amount of fossils and also the species number seem to be increased.

The amount of terrigenous fragments increase again nearby in the middle horizon of this outcrop, and in this horizon thin noncalcareous sand beds are sometimes partly intercalated.

Between this horizon and the upper horizon 7–8 m above, *Operculina* and *Cycloclypeus* are found sporadically. Therefore, it seems that this part is correlated with the A Member. On the other hand, this part also shows different characteristics; the amount of foraminifers is less than that of the A Member in other areas, and *Operculina* is observed abundantly in the lower horizons rather than in this part. Moreover, algal fragments are found commonly and coralline debris is sometimes contained in this part. These characteristics seem to be intermediate between the A and B Members. It is necessary to establish more sufficient stratigraphical divisions and the correlation of this outcrop with those of other areas should be studied more precisely in the future.

7. Tako-yama

By means of the geological survey nearby, it is confirmed that noncalcareous sand beds are buried below this outcrop, the calcareous facies occupies most of this outcrop (Fig. 8).

A sand bed of 0.5–1 m in thickness containing many of the basement lithoclasts is intercalated in the middle horizon of the outcrop, and between the base of this sand bed and the upper horizon about 6 m above, *Operculina* and *Cycloclypeus* are abundantly yielded. Therefore, the writer correlated this part with the A Member of the Upper Formation. Both the A and B Members decrease in thickness northward (toward right in Fig. 8), while the biolithites of the C Member increase in thickness. Biolithitic limestones intertongue with the bioclastic limestones in the Lower Formation. The sediments of the Ryukyu Group are dislocated frequently by faults in this outcrop, while a plane of about 75 m above sea level is developed which uniformly cuts these geological structures.

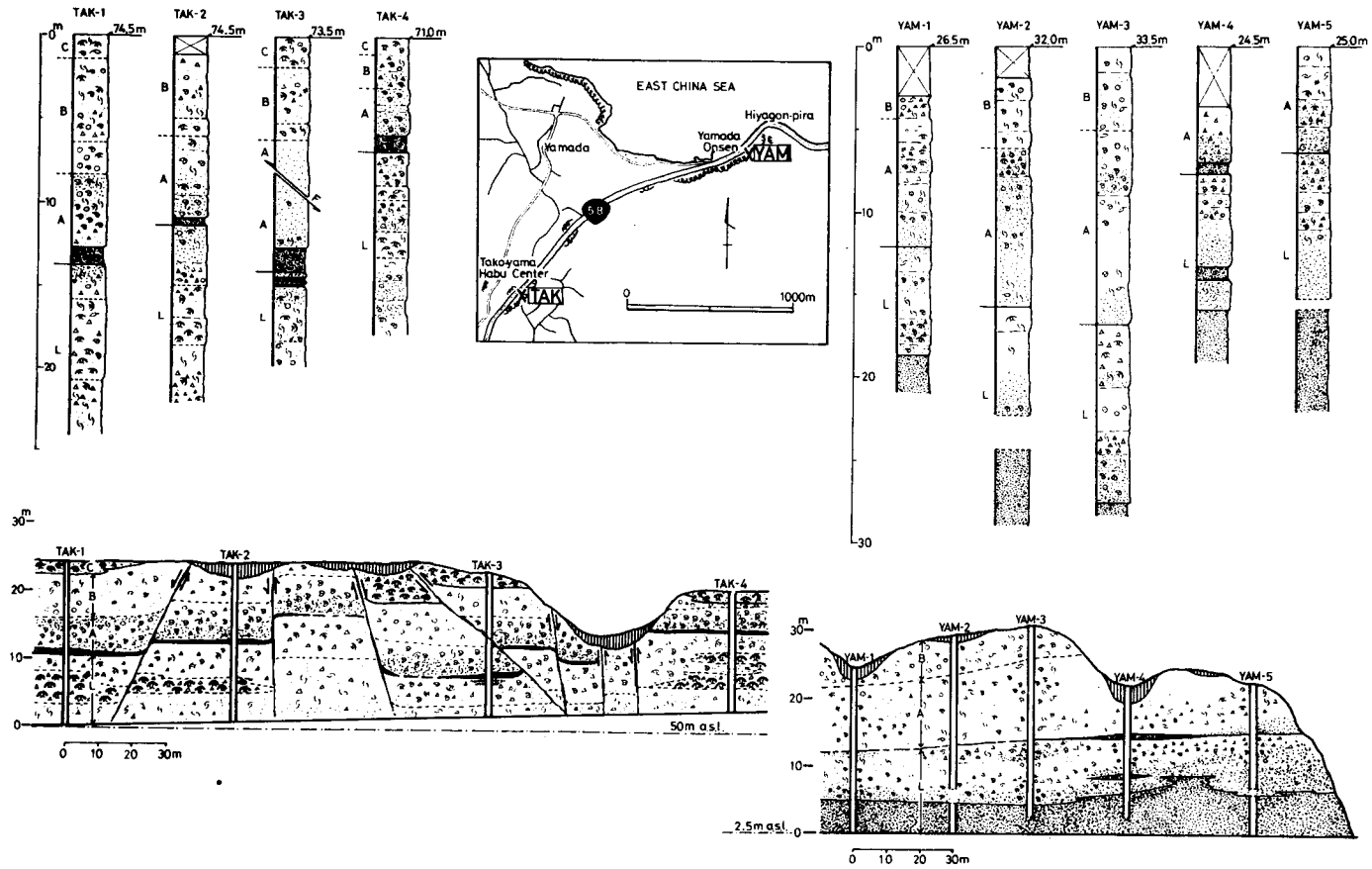


Fig. 8. Sketches and columnar sections of the outcrops at Takoyama (TAK) and Yamada-onsen (YAM).

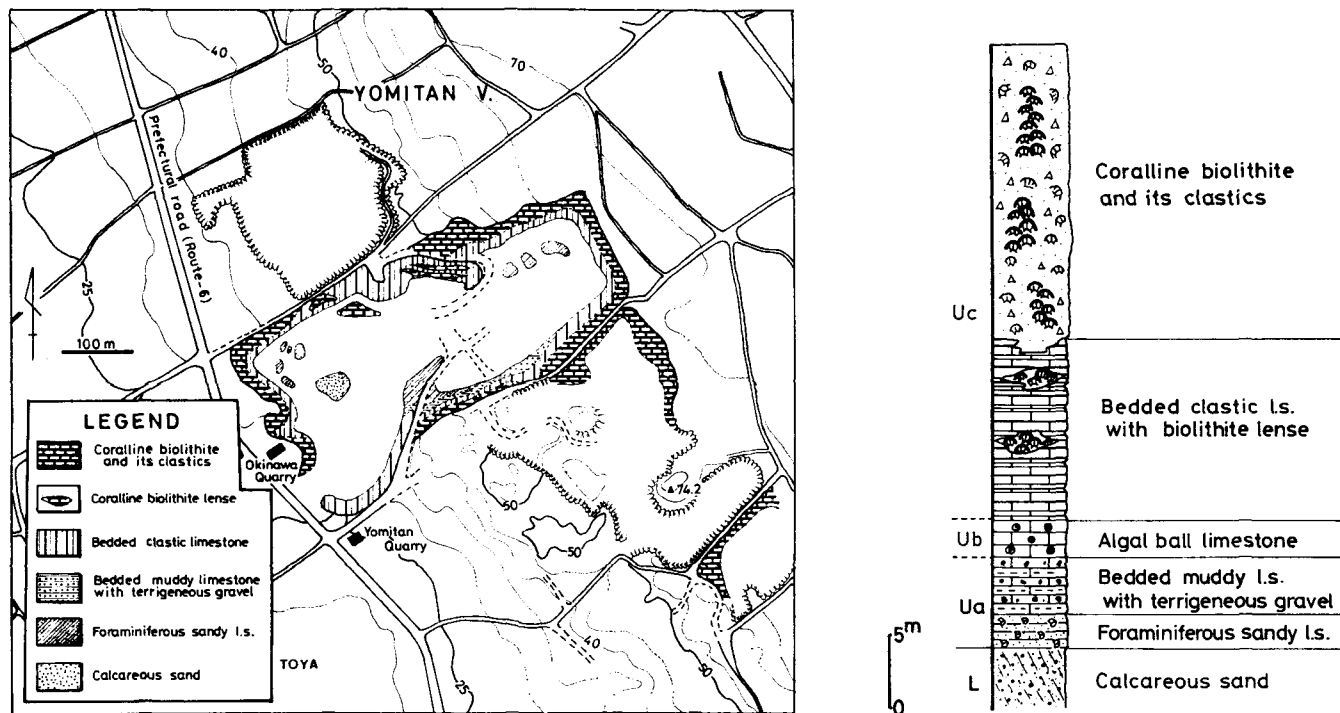


Fig. 9. Sketch map and columnar section of Yomitan quarry.

8. Yomitan

The limestone quarry of Yomitan was designated as the type locality of the Yontan limestone by FLINT *et al.* (1959). The writer, however, regards most of this limestone in this quarry to the C Member of the Ryukyu Group, notwithstanding its large thickness (Fig. 9). Therefore, it may be concluded that the Yontan limestone of FLINT *et al.* is synonymous with the writer's C Member in this paper.

At this quarry, the writer observed the conformable relation of the C Member with the lower beds. Therefore, it should be discarded to postulate the presence of the unconformity between the Yontan limestone and the Naha formation as pointed out by FLINT *et al.* (1959).

Near Zakimi Castle, the northern part of Yomitan Village, the coralline biolithite overlies unconformably the noncalcareous sand and gravel beds which are correlated with the noncalcareous sand beds of the outcrop of Yamada-onsen. On the other hand, the coralline biolithite seems to be corelated with the C Member. The stratigraphical relation of the local unconformity between the Lower Formation and the C Member of the Upper Formation is similar to that in the eastern part of Motobu Peninsula.

9. Makiminato

Well stratified calcareous sand beds and bioclastic limestone with numerous quartz grains are distributed in Makiminato, Urasoe City. They are rich in mollusks, bryozoans, echinoderms and brachiopods, and similar lithologically to the Lower Formation of Katsuren Peninsula and the southern part of Okinawa-jima.

Besides, though it is hard to approach the good outcrops of the Machinato limestone of FLINT *et al.* (1959) in this area, as already mentioned, a few small outcrops of the cross laminated calcarenite can be seen in the former foreigner's residential district nearby the shore. The limestone is similar to the Minatogawa Limestone having abundant foraminifers and intraclasts, but the grain size of the former is finer than that of the latter.

C. Discussion

As mentioned above, for the stratigraphy of the Ryukyu Group, the main part of the "Ryukyu Limestone", the writer's division is shown to be available everywhere in Okinawa-jima, if some local differences in lithology are disregarded. Thus, the writer's Ryukyu Group is considered to be approximately equivalent to the Naha formation plus the Yontan limestone formation of FLINT *et al.* (1959). In this sense, the algal limestone beds of the horizon marker by FLINT *et al.* (1959) and SHOJI (1968) seem probably to be equal to the B Member in the writer's stratigraphical division; even though, the algal limestones are also recognized in other horizons of the Ryukyu Group. In addition, the local differences of the mode of occurrence of fossil algae and the lithology of the B Member make it difficult to discriminate definite horizons of the algal beds stratigraphically. Nevertheless, the *Cycloclypeus-Operculina* swarm bed is usually recognized as one definite horizon everywhere, with remarkable petrographic characteristics.

Table 4. Tentative correlation of the late Pliocene and the Quaternary formations of the southern half of the Ryukyu Islands

Age Group	OKINAWA				YORON	KUME	AGUNI	MIYAKO	TARAMA	ISHIGAKI	TAKETOMI	KOHAMA	IRIOMOTE	HATERUMA	YONAGUNI	
	Kunigami	Motobu	Nakagami	Shimajiri	OKIMURA 1976	(OKINAWA QUAT RES. G 1976)		(YAZAKI 1976)				(SHINOHARA & KIZAKI 1976)				
HOLOC.	Dune sand, beachrock, Recent reef, etc.							Nishihama saki Dune Sand	Tomidai Ls.	Shiraho Dune Sand	Dune sand, beachrock, Recent reef, etc.					
	Raised coral reef, beach deposits (1-3)				Raised reef (10-11) Iribishi Ls. (2)		Raised reef (10) Shiratori saki Ls.		Maedomari Ls.		2-3m high bench					
PLEISTOCENE	Kyoda terrace				(Numbers in parentheses indicate the height of terrace surfaces, in meter)						(5-7) Kaburagi (10) L.s.	(15-20)	(15-20)	(15-20)	(15-20)	
	(60)				(30-50)				(40-50)	(60)			(150-60)	(45)	(40-50)	(40)
Early	Upper F				Upper F				Hirara L.s.		bioclastic i.s.		coralline bioclastic i.s.		coralline i.s.	
	Upper B				Upper B				Upper		Amagawa L.s.		Ururo L.s.		brecciated i.s.	
Middle	Upper A				Upper A				Middle		Cyclocypæus i.s.		Operculina coralline bioclastic i.s.		bioclastic i.s.	
	Lower F				Lower F				Lower		Bura Clay		calc. sand		sandy silt	
Late	Nakoshi Sand				Chinen Sand				Bora L.s.							
	Goga Gravel				Shinzato Tuff											
PLIOC.	Yonabaru F.															
Shimajiri Group																

"Ryukyu Limestone" of Okinawa-jima, South Japan

Further, the continuity of the *Cycloclypeus-Operculina* bed is verified by the writer not only in Okinawa-jima but also in other islands of the Ryukyu Islands. Therefore, it is probable that the stratigraphy of the "Ryukyu Limestone" established in Okinawa-jima is applicable to so-called "Ryukyu Limestone" in other islands throughout the Ryukyu Islands. In this way, the writer compiled the stratigraphy of "Ryukyu Limestone" in a correlation chart of Table 4 on the basis of his data together with others.

IV. Sedimentological Study of the "Ryukyu Limestone"

In order to consider the sedimentary environment of the "Ryukyu Limestone", the writer made petrographical observations and fossil analysis on the samples of main outcrops and drilling cores under the optical microscope. The results will be described below briefly.

A. Textural Components

The fundamental textural components of the "Ryukyu Limestone", are classified as follows: matrices, framework grains (allochemical grains or allochems, by FOLK, 1959) and pores.

The matrices in the writer's usage imply not only the microcrystalline calcite ooze but also sparry calcite cement. They are easily distinguished from each other under the microscope. Although diagenetic fabrics are observed in some cases and seem to explain only partially the hysteresis of the limestone, the writer could not find out the pertinent facts on this point.

The constituents of the framework grains are occupied by skeletal grains of fossil for the most part. Besides, the presence of lithoclasts and quartz grains of the terrigenous fragments are confined to some specific horizon of the Ryukyu Group. On the contrary, it is characteristic that the Minatogawa Limestone contains well rounded intraclasts abundant and sometimes lithoclasts of the Ryukyu Group. Pellets are rarely found, and oolites have not been found yet in the "Ryukyu Limestone".

As for fossils, though it is necessary to distinguish detrital skeletal grains from skeletons *in situ*, it is almost impossible in practice to discriminate them in thin sections. Therefore, the writer discriminated the clastic limestones from the biolithites on the occasion of sampling, and made an analysis in the laboratory only for the former in order to know the constituents of the skeletal grains.

B. Method of Fossil Analysis

Even though the skeletal grains which constitute most of the "Ryukyu Limestone" are supposed to be detrital, they play an important role in the inference of the sedimentary environments and also in the accurate correlation of the stratigraphical sequences.

From the viewpoint stated above, the writer tried with his colleagues to establish the method for the recognition of the skeletal constituents of the "Ryukyu Limestone" more objectively and quantitatively, as far as possible. Consequently, two methods

used here are considered. Though these methods connote many problems to be solved and improvements to be made**, it seems that these methods contribute to objective and quantitative studies on the skeletal constituents of those materials.

Method-A: Counting each skeletal grain as one unit, and after summing them up the composition of each taxon is shown by percentage.

In order to keep the stability in the analytical value, the total number of skeletal grains should be counted more than 500. Though the amount of indeterminable skeletal grains often reaches to the value more than thirty percent, the outline of the quantitative distribution of main taxa can be known from the determinable skeletal grains.

Method-B: Using a mechanical stage, move the thin section sideways and forwards and backwards in equal distances of 0.2 mm each, and identify constituents just under the cross hair. Then summing up the number of the points, the composition of each constituent is shown in percentage.

In this method, all of the constituents including pores are calculated. But at this time, as the problem on the origin of the pores is still unsolved, the proportion to the value subtracted of the point numbers of pores from the total count is substituted as the approximate proportion of each constituent.

By means of this method, the ratios of the microcrystalline calcite matrix, the sparry calcite cement and allochemical grains which are fundamental components for petrographical classification of limestone, can be represented by numerical values. Therefore, this method can be applied to the fossil analysis as well as the petrographical description. For keeping the stability in the analytical value, the total count is recommended to be more than 1,000 points in the case of the calculation of those three component ratios and more than 2,000 or 2,500 points in the case of the examination of the skeletal proportion.

C. Discussion

The results of the analysis are summarized in Fig. 10-15.

Only SHOJI (1968) has carried out a study on the microscopic petrography and sedimentology of the "Ryukyu Limestone". Though it was conventional SHOJI stated that some sedimentary subcycles are present in each limestone of gravel, sand, sparite, sparmicrite and micrite succession, and there are three cycles in the Naha limestone, two cycles in the Yomitan limestone, and one in the Machinato limestone.

** In Method-A, it is impossible to denote quantitative comparison among different samples in the strict sense, because there is a certain difference in the amount of skeletal grains in each sample. In the case of the "Ryukyu Limestone", however, this anxiety can be negated, for the skeletal grains show high occupancy in most samples. In Method-B, there is suspicion that the large fragments show a large value of proportion, because the value of the constituent proportion obtained by this method is calculated as the ratio of area. Furthermore, as for both methods, all skeletal grains are regarded as objects having equal valuation whether the grain is broken or not, because the observation is made only on one section of each skeleton. Therefore, the analytical value may also be affected by the differences in the structural intensity of the individual skeleton.

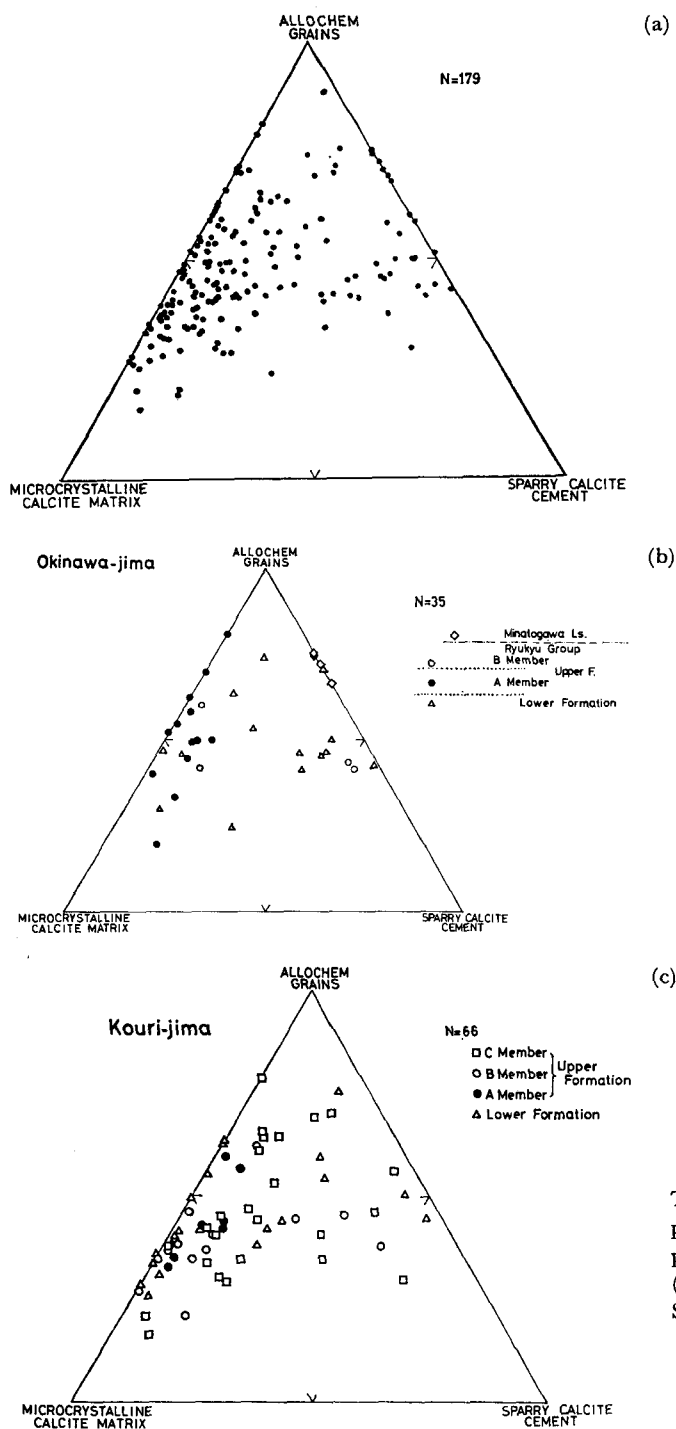


Fig. 10.
Triangle diagrams showing the pro-
portion of three fundamental com-
ponents. (a) All analyzed samples
(b) Samples of Okinawa-jima (c)
Samples of Kouri-jima.

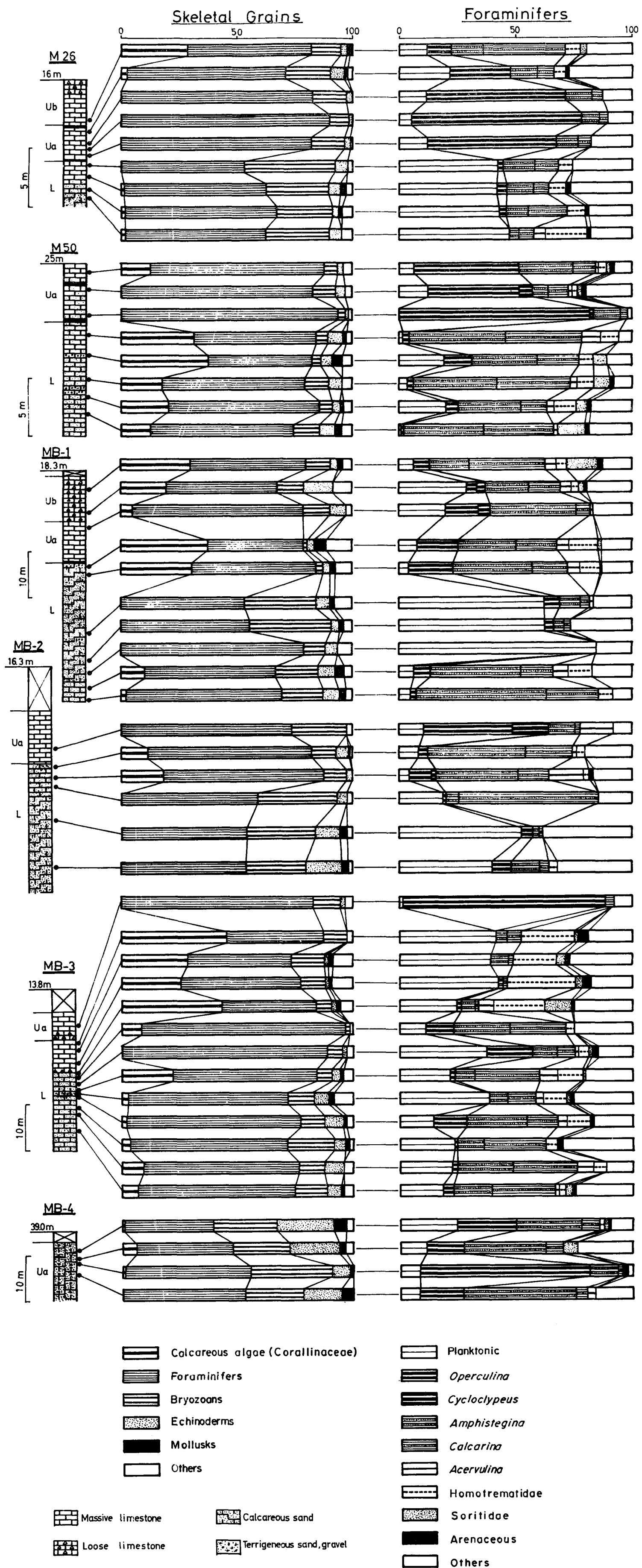


Fig. 11. Diagrams of skeletal components of some columnar sections in Motobu Peninsula (analyzed by Method-A).

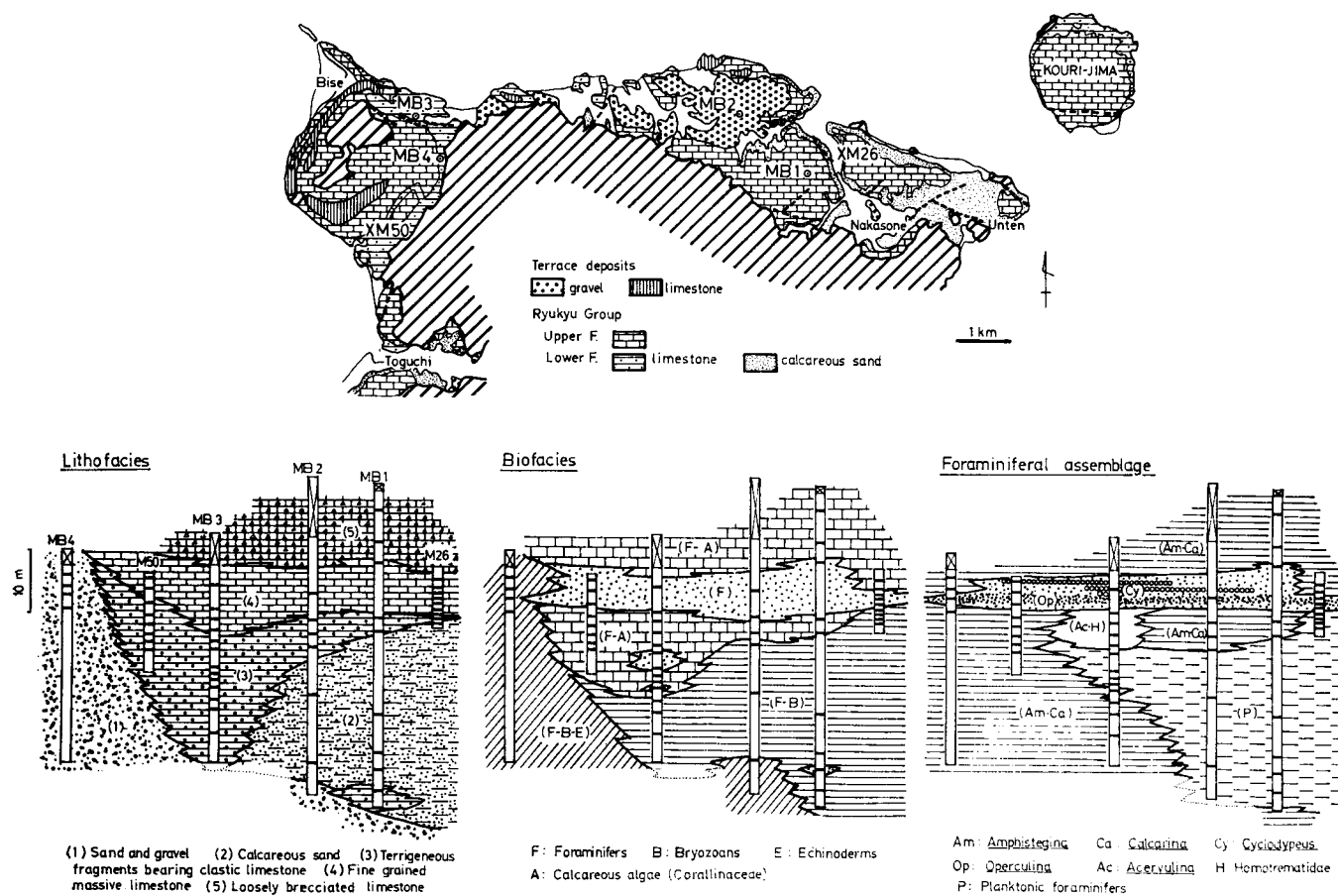


Fig. 12. Geologic outline of the northern part of Mobuto Peninsula (above), and lithological and paleontological correlation among the sections shown in Fig. 11, (below).

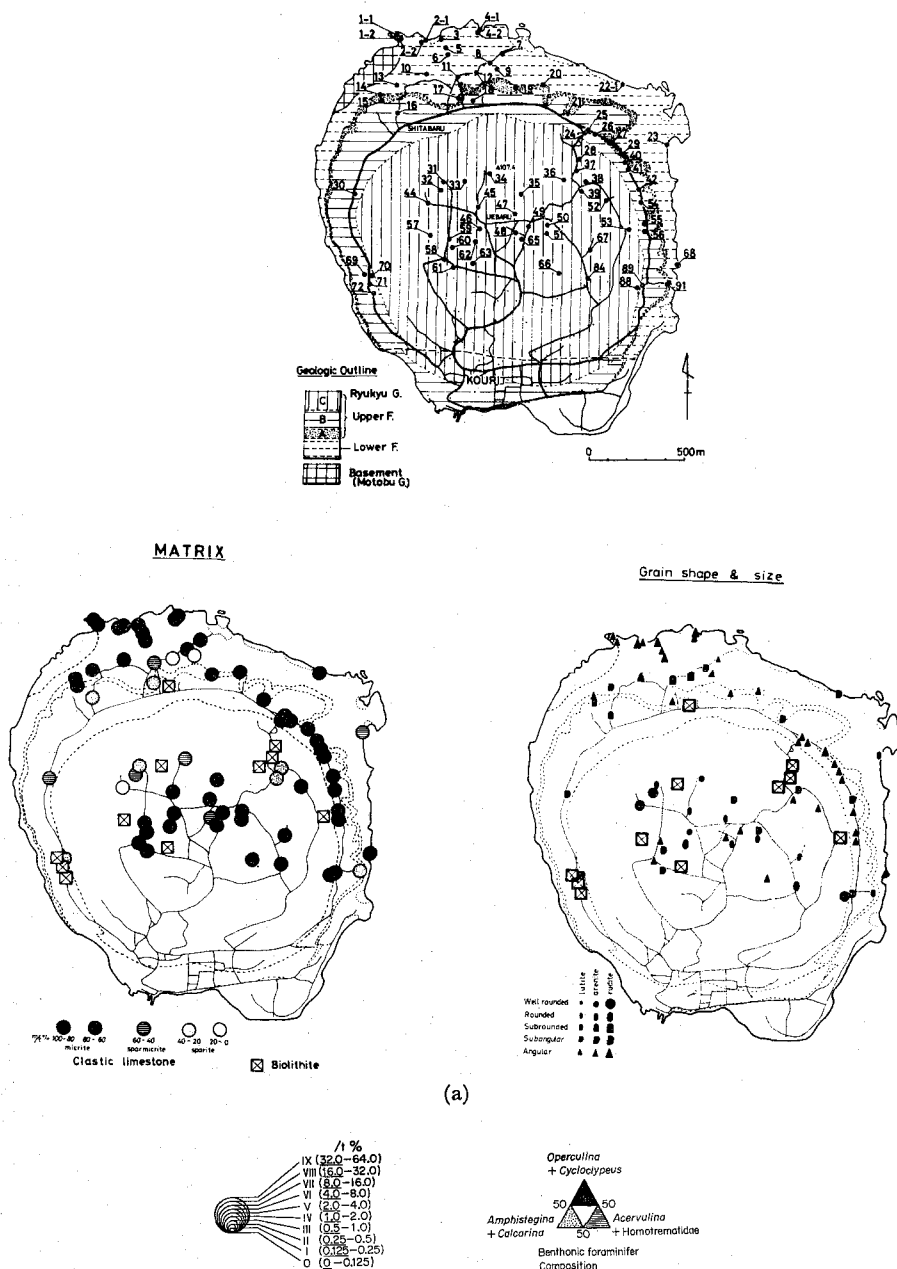


Fig. 13. Distributive pattern of each component of the Ryukyu Group of Kouri-jima. (a) Matrix and shape and size of grains. (b) Skeletal components (analyzed by Method-B).

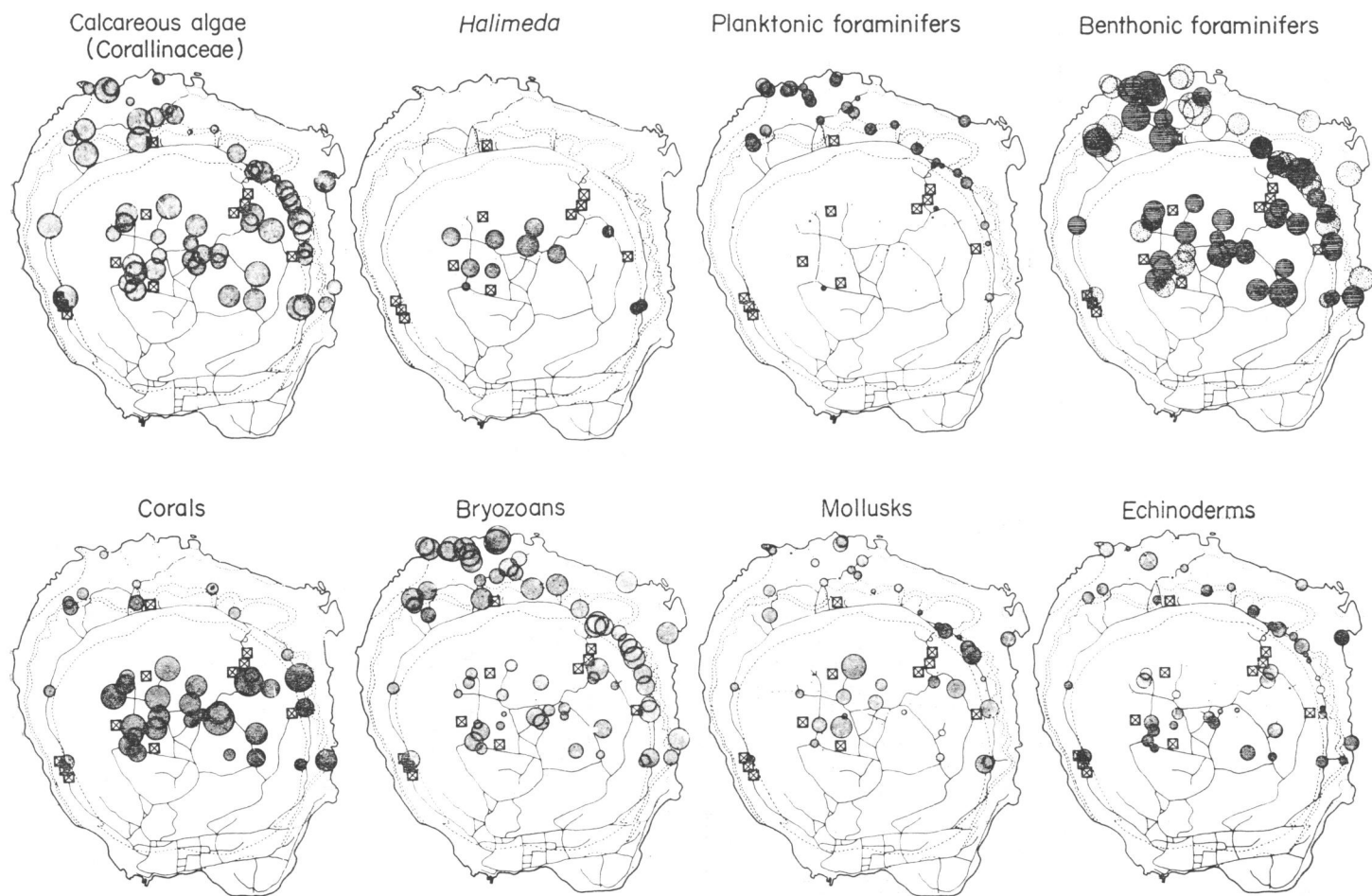


Fig. 13. (b)

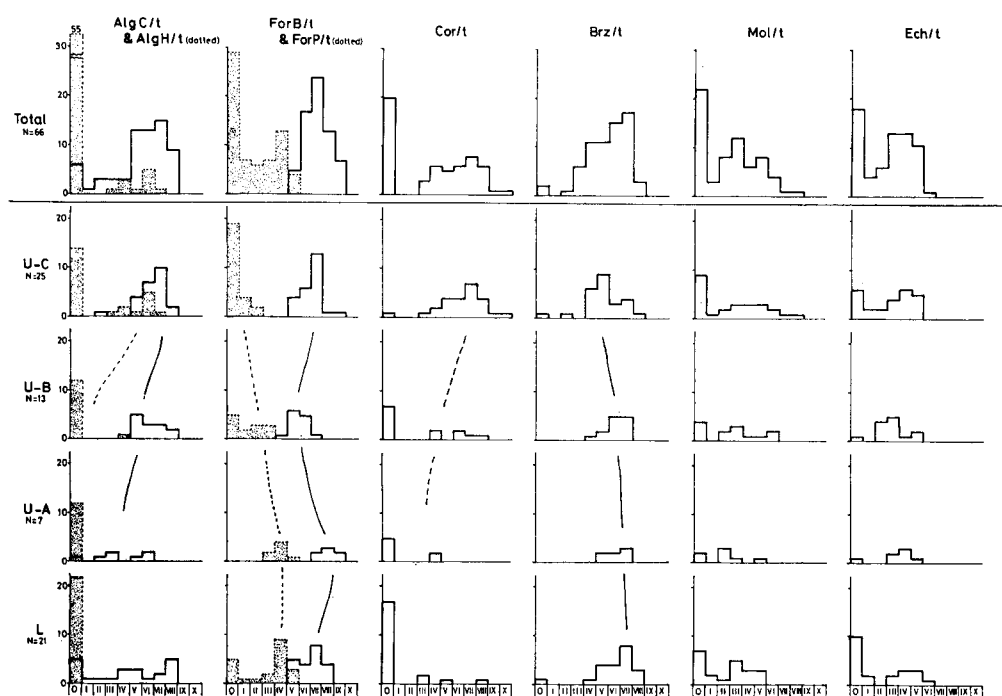


Fig. 14. Stratigraphical distribution of the skeletal components of the Ryukyu Group in Kouri-jima. Lateral axis shows content: 0; less than 0.125%, I; 0.125–0.25%, II; 0.25–0.5%, III; 0.5–1%, IV; 1–2%, V; 2–4%, VI; 4–8%, VIII; 8–16%, VIII; 16–32%, IX; 32–64%, X; more than 64% to total counts without pores (t). Longitudinal axis shows frequency. AlgC; Corallinae, AlgH; *Halimeda*, ForB; Benthonic foraminifers, For P; Planktonic foraminifers, Cor; Corals, Brz; Bryozoans, Mol; Mollusks, and Ech; Echinoderms.

SHOJI considered the formation of those cycles as the reflection of the developmental process of the coral reef controlled by sea level change or tectonic movement, and regarded the microcrystalline limestone as product of the last stage of each cycle, that is, a stagnant shallow lagoon environment.

As mentioned formerly, MACNEIL's stratigraphical division on which SHOJI relied is different from the writer's. Therefore, it is difficult to compare directly SHOJI's work with the results of the writer's analysis. But, on the constituent of matrices, to which SHOJI paid much attention, the following facts must be pointed out from the results of the writer's analysis.

(a) In the matrices of the "Ryukyu Limestone", microcrystalline calcite is the dominant constituent in general (Fig. 10a), and the typical spartite is observed to be limited in the Minatogawa Limestone and a part of the Ryukyu Group (Fig. 10b, c).

(b) Even in the same horizon (for example, in the B Member or in the C Member

of the Upper Formation of the Ryukyu Group, shown in Fig. 10b, c), the constituents of matrices are variable in accordance with the difference of sampling point.

(c) The A Member of the Upper Formation of the Ryukyu Group is represented generally by microcrystalline limestones (Fig. 10b, c).

From these facts, the writer does not agree with SHOJI's opinion that the "Ryukyu Limestone" consists of many sedimentary subcycles. According to the writer's consideration, the Ryukyu Group itself, the main part of the "Ryukyu Limestone", is a product of a large sedimentary cycle as a whole. But in general, in this large cycle, there are small two cycles which are regarded as corresponding to the Lower and the Upper Formations respectively.

From this viewpoint, the writer gives his consideration to explain the sedimentary environment of the Ryukyu Group.

1) With good correlation between lithofacies and biofacies, the sedimentary facies of the Lower Formation varies from place to place. For example, in Motobu Peninsula, as shown in Fig. 12, the biofacies change from [foraminifers-bryozoans-echinoderms] to [foraminifers-bryozoans], and [foraminifers-calcareous algae] in parallel with the change of lithofacies from abundant terrigenous fragment situation to poor ones.

2) The correlation between lithofacies and biofacies mentioned above can be

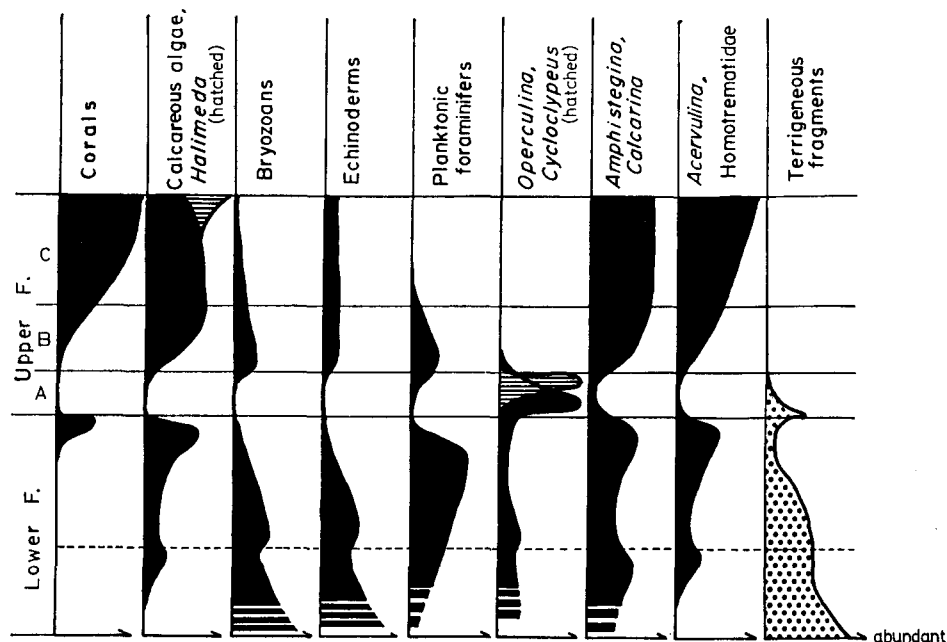


Fig. 15. General tendency of the stratigraphical distribution of skeletal components and terrigenous fragments, on the basis of field observation and indoor analysis.

generally ascertained in vertical change (Fig. 12) as well. It suggests that the sedimentary environment of the Lower Formation changed from the sea unfavorable for coral reef forming to those of favorable. Actually, this is attested by the presence of coralline biolithite at the top horizon of the Lower Formation.

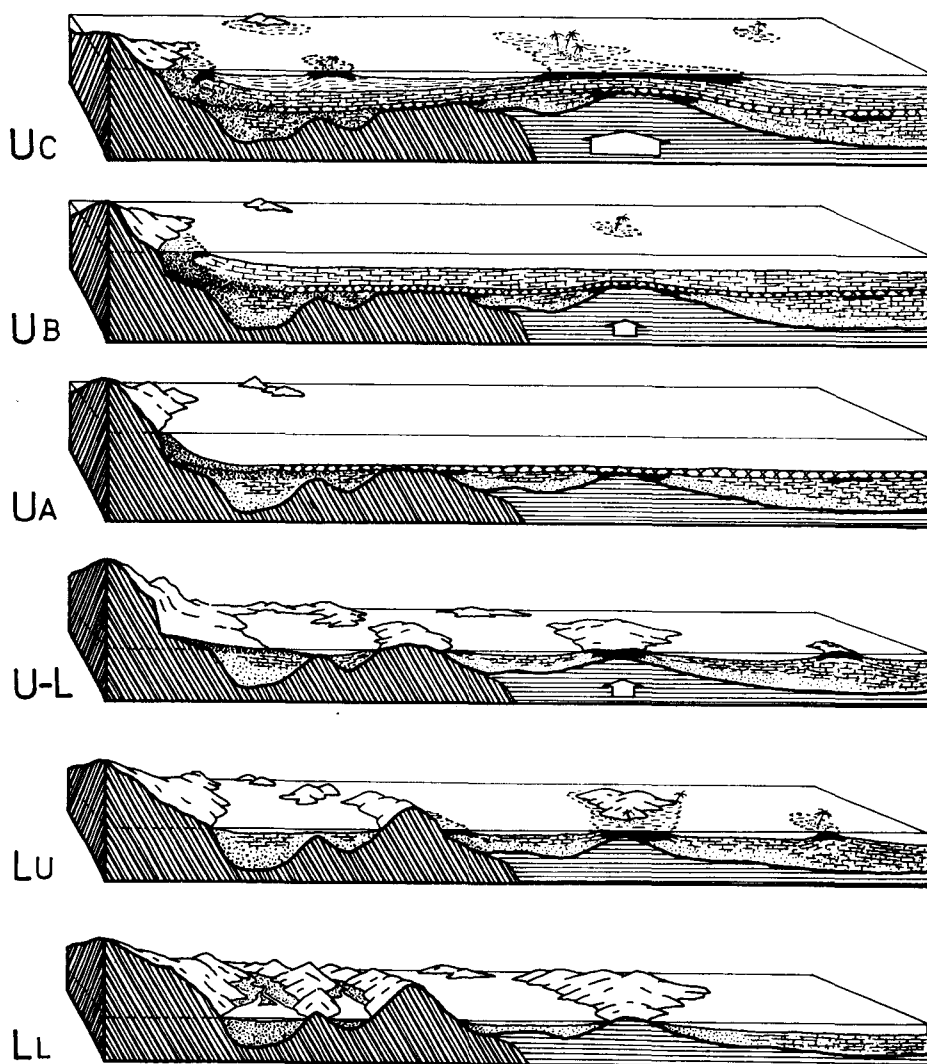


Fig. 16. Schema of the sedimentary process of the Ryukyu Group. LL and LU are the stages of the lower and the upper parts of the Lower Formation respectively, and UA, Ub and Uc are the stages of the A, B and C Members of the Upper Formation respectively. U-L is the interval stage between the Lower and the Upper Formations. Showing the imaginative section in Central Okinawa, E-W trend.

3) During the deposition of the A Member of the Upper Formation, the sedimentary environment turned to those of unfavorable for coral reef forming. This inference is based on the fact that confined species such as *Cycloclypeus* and allies of deeper environment are chief components of the biofacies of the A Member and are rich in number as shown in Fig. 11. As for the A Member, some other characteristics were already mentioned, and they are as follows; terrigenous fragments are often contained in the lower part of the A Member, and the thin layers of terrigenous reddish brown clay are sometimes intercalated in the *Operculina* swarm part, and *Cycloclypeus* are often yielded in swarm immediately above the *Operculina* swarm part. These facts suggest that the coral reef environment deteriorated rapidly due to the inflow process of lithoclasts and residual clay from the land area, and the increase of the depth of the sea.

4) In the stage of the Upper Formation, the area of sedimentation expanded rapidly more than the Lower Formation as mentioned in the former chapter. The fact that the uniform stratigraphical sequence of the Upper Formation is tracable in wider areas than those of the Lower Formation, suggests the advent of a uniform sedimentary environment by transgression. Succeedingly the sea became gradually shallower after the A Member stage, and then in the C Member stage, the typical coral reef environment was initiated. This explanation is supported by the increase of *Coralinaceae* and the decrease of bryozoans upwardly in the Upper Formation, and the rapid increase of *Halimeda* and corals in the C Member (Fig. 13, 14). The decrease in the number of planktonic foraminifers towards the upper in the Upper Formation (Fig. 13, 14) also suggests the environmental change from open sea to reef.

The stratigraphical distribution of the fossils in the Ryukyu Group is shown schematically in Fig. 15, and the environmental changes during the sedimentation of the Ryukyu Group are shown in Fig. 16.

Incidentally, the Minatogawa Limestone Formation is considered to be the sediments of an extreme shallow environment affected by constant wave action or a sub-aerial sand beach environment in part, because these limestones are represented by sparite and all grains are well rounded without exception (Pl. 16, Fig. 1).

V. General Discussion on the Quaternary Geohistory of the Ryukyu Islands

A. Age of the Ryukyu Group

There are very few reports of fossils available for determining the age of "Ryukyu Limestone". But the following discussion will be possible.

YABE and HATAI (1941) reported the occurrence of *Amussiopecten praesignis* and *Pecten naganumanus* in the "Ryukyu Limestone" in Naha City. Though they described

these fossil horizons with uncertainty, it is probable that they were yielded from the Lower Formation of the Ryukyu Group in the writer's division. In Honshu, *A. praesignis* is known from the Pliocene and the Lower Pleistocene, and *P. naganumanus* is abundant especially in the Lower Pleistocene. Therefore, these mollusks support HANZAWA's opinion (1935) that the age of the "Ryukyu Limestone" is Late Pliocene or from Late Pliocene to Early Pleistocene.

On the other hand, the uppermost part of the Shimajiri Group, below the Ryukyu Group, is considered Lower Pleistocene according to the latest micropaleontological works. As for the planktonic foraminifers, NATORI *et al.* (1972) reported the first appearance of *Globorotaria* (*Globorotaria*) *truncatulinoides* from the top of the Shinzato Formation (upper Shimajiri), and IBARAKI and TSUCHI (1975) reported abundant occurrences of that species from the Chinen Sandstone (upper-most Shimajiri). On the calcareous nannoplankton, NISHIDA (1973) recognized that *Cyclocolithus macintyreii* and *Discoaster brouweri* range up to the overlying Chinen Sandstone. He described the appearance of *Gephyrocapsa oceanica* from the Nakoshi Sand Beds.

These reports suggest that the age of the Chinen Sandstone is the Early Pleistocene. Therefore, it is certain that the lowest horizon of the Ryukyu Group does not go back to the Pliocene.

Several vertebrate fossils have been obtained from cave or fissure deposits in the "Ryukyu Limestone" (Table 5). Among them, *Metacervulus astylodon* is most abundant, and is regarded as an important element of the paleovertebrate fauna of the Ryukyu Islands.

M. astylodon was also reported from the Lower Formation of the Ryukyu Group of Ishigaki-jima (FOSTER 1965; OTSUKA and HASEGAWA, 1973). The "*Muntiacus*" that occurred in the basal part of the Ryukyu Group (SHIKAMA and OTSUKA, 1971) is considered to be identified as *Metacervulus astylodon*, too (OTSUKA and HASEGAWA, 1973).

According to TOKUNAGA and TAKAI (1939), *M. astylodon* of the Ryukyu Islands and *M. kendengensis*, a member of the Trinil mammalian fauna of Java, are both the nearest descendants of *M. capreolinus* which occurs in the Yushe Series (Zone II and Zone III, Villafranchian equivalent), South-Eastern Shansi, China. And they considered that *M. kendengensis* is a relative of living muntjacs of Southeast Asia and Taiwan, while extinct *M. astylodon* was the insular form in Ryukyu.

Based on their opinions, the lowest horizon of the Ryukyu Group deduced from *M. astylodon* may go back to Early Pleistocene.

The elephantoid molar teeth discovered from the cave deposits of Miyako-jima and from the "Ryukyu Limestone" at Kyan-misaki, Southern Okinawa, are also worthy of notice among the vertebrate fossils in the Ryukyu Islands. Hitherto, two specimens have been discovered in Miyako-jima; one was reported by TOKUNAGA (1940) as a molar of *Palaeoloxodon namadicus* or *Elephas trogonterii* and the other was reported by OTSUKA (1941) as a molar of *Palaeoloxodon*?. After the re-examination of the site and

Table 5. List of fossil vertebrates of the Ryukyu Islands

<u>Mammalia</u>	
<u>Rodentia</u>	
<i>Diplothrix legata</i> (THOMAS)	Miyako-jima (Amagawa and Tanabaru Caves) Okinawa-jima (Minatogawa fissure)
<u>Artiodactyla</u>	
<i>Capreolus miyakoensis</i> OTSUKA	Miyako-jima (Amagawa Cave)
<i>Capreolus</i> sp.	Miyako-jima (Tanabaru and Nakabaru Caves)
<i>Metacerrulus astylodon</i> (MATSUMOTO)	Miyako-jima (Amagawa Cave) Ie-jima (caves) Okinawa-jima (fissures and Ryukyu Group) Ishigaki-jima (Ryukyu Group)
<u>Proboscidea</u>	
<i>Trilophodon</i> sp.	Miyako-jima (Shimajiri Group)
<i>Palaeoloxodon</i> or " <i>Archidiskodon</i> "	Miyako-jima (Tanabaru Cave) Okinawa-jima (Ryukyu Group)
<u>Reptilia</u>	
<u>Chelonia</u>	
<i>Tetudo</i> cf. <i>emys</i> SCHLEGER et MULLER	Miyako-jima (Amagawa Cave) Okinawa-jima (caves)
<i>Clemmys</i> cf. <i>mutica</i> (CANTON)	Miyako-jima (Amagawa Cave)

by the articles ; TOKUNAGA and TAKAI (1939), TOKUNAGA (1940), OTSUKA (1941), FOSTER (1965), OTSUKA and HASEGAWA (1973), HASEGAWA *et al.* (1973), NOHARA and HASEGAWA (1973)

the photographs of those fossil molars, KAMEI (1970) suggested that these were "*Archidiskodon*" rather than *Palaeoloxodon*.

The fossil horizon of Kyan-misaki is the B Member of the Upper Formation in the writer's division. NOHARA and HASEGAWA (1973) identified it as a fragmentary molar of *Palaeoloxodon*? sp., but they stated that the possibility of "*Archidiskodon*" still remains.

If these elephants are "*Archidiskodon*", it is possible to correlate the Ryukyu Group with the upper part of the Osaka Group and the upper part of the Kazusa Group. The highest horizon of the Ryukyu Group, therefore, is considered to be Early and early Middle Pleistocene.

Additionally, it was reported by SHIKAMA *et al.* (1975) that the Cho-chen fauna of Taiwan, Early and Middle Pleistocene in age, is represented by *Mammuthus armeniacus taiwanicus* and *Elephas hysudricus*. The relation between the fossil elephants of Taiwan and the Ryukyu Islands is a very interesting problem.

Based on the paleontological aspects mentioned above and the geological relation

between the terrace formations and the Ryukyu Group, the writer considers the age of the Ryukyu Group as Early to early Middle Pleistocene. It may be possible that the Ryukyu Group is correlated with the upper part of the Osaka Group.

After the general report of Th^{230} - Pa^{231} ages of the "Ryukyu Limestone" by KONISHI *et al.* (1974), all measured values are included in Late Pleistocene. But it seems that these values are inconsistent with paleontological evidence and the results of the geohistorical considerations of the Ryukyu Islands mentioned below.

B. "Uruma Crustal Movement"

Many faults caused network dislocation in the Ryukyu Group, and consequently, many tilting blocks are formed (Fig. 7). In so far as Southern Okinawa area is concerned, the *Cycloclypeus* bed is distributed in various heights from near sea level to about 155 m above sea level due to such dislocation. Covering the area from Central to Southern Okinawa, a dome structure with a long axis of NE to SW trend is confirmed (Fig. 17), which is called the Nakagusuku Dome (FLINT *et al.*, 1959). The fault system of these districts is supposed to be undergone through the destruction process of the Nakagusuku Dome (KIZAKI and TAKAYASU, 1976; TAKAYASU, 1976b).

The fault system which dislocate the Ryukyu Group are also developed in Miyakojima and Kikai-jima, and those structures are clearly recognized from topographical features. In these areas without exception, the thick Shimajiri Group exists below the Ryukyu Group. This fact suggests that the tectonic movement such as dome forming and the fault system development is closely related with the extermination of the sedi-

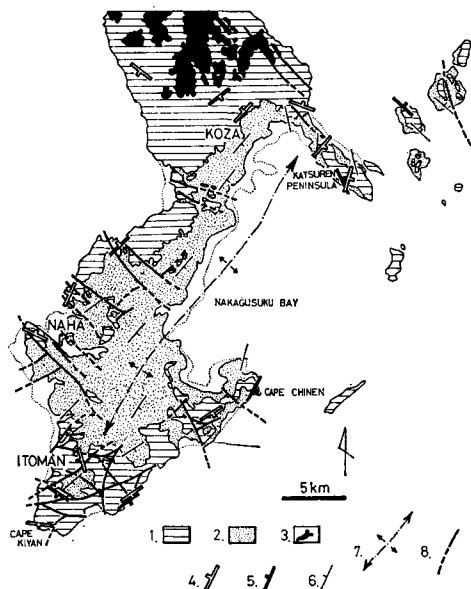


Fig. 17. Structural outline of Central and Southern Okinawa (TAKAYASU, 1976 b). 1; "Ryukyu Limestone", 2; Shimajiri Group, 3; Basements, 4; General structure of the Ryukyu Group, 5; General structure of the Chinene Sandstone, 6; General structure of the Shimajiri Group, 7; Axis of the Nakagusuku Dome, 8; Fault.

mentary basin being continued from Neogene time.

It is accepted by all researchers that the relation between the Shimajiri Group and the Ryukyu Group is generally represented by an angular unconformity. This relation is clearly observed in the west coast of Okinawa-jima, where the Shimajiri Group inclines to the east or southeast, while the Ryukyu Group has gentle structure or slightly inclines to the west in direction. In the east coast of Central and Southern Okinawa, however, both of the Groups incline to east or southeast gently. So, it is possible to say that the relation between the two Groups is represented as a whole by an indistinct unconformity or disconformity. In several places, the Ryukyu Group is successively without any marked break with the Chinen Sandstone, as in the cases of Chinen Peninsula and Henza-jima, off the coast of Katsuren Peninsula.

The writer, with reference to these significant relations, tried to explain the conversion from the "Shimajiri Sea" to the "Ryukyu Coral Sea". It was explained by means of the shifting of the upheaval center from west to east (Fig. 18; KIZAKI and TAKAYASU, 1976; TAKAYASU, 1976b). That is, at the close of the "Shimajiri Sea" stage, the upheaval center of the area where was to the west of Okinawa-jima became to be covered widely by shallow facies, which was represented by the uppermost part of the Shimajiri Group (LEROY, 1965; NOHARA, 1976). Succeedingly, the sedimentary center of the basins was shifted toward the east. As a result, the Shimajiri Group was characterised in having the structure with uniform inclination to the east or southeast, and thus the emerged areas came to be under erosion. Succeedingly, the "Ryukyu Coral Sea" was initiated by the next transgression.

During the "Ryukyu Coral Sea" stage, the upheaval center was shifted further to the east, and the embryo of the Nakagusuku Dome became to exist. The local unconformity present between the Lower and Upper Formations in the Ryukyu Group, as mentioned in Chapter III, might be the result of that dome forming. Further, the development of the coral reef in the C Member of the Upper Formation may also be accompanied with the appearance of the shallow environment due to the accentuation of the Nakagusuku Dome. Later, after the collapse of that dome by faulting, the present configuration of Okinawa-jima was brought about. A series of these tectonic movements is called the "Uruma*** Crustal Movement" (OKINAWA QUATERNARY RESEARCH GROUP, 1976; KIZAKI and TAKAYASU, 1976; TAKAYASU, 1976b).

Taking a general view of the Ryukyu Group, it is possible to say that the Plio-Pleistocene sea of this area went to extinction step by step through the course of the "Uruma Crustal Movement", and the estate of the "Ryukyu Coral Sea" of the last stage is the Ryukyu Group itself.

Though the details of the "Uruma Crustal Movement" will be discussed in another paper, it is possible to infer that similar tectonic movement had an influence throu-

*** "Uruma" means coral island in the dialect of Ryukyu.

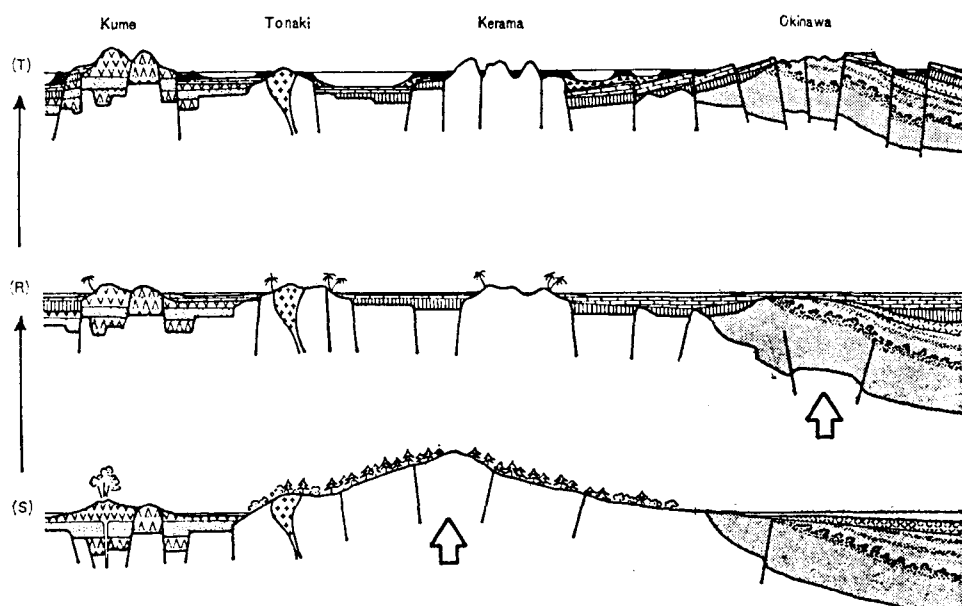


Fig. 18. Schema showing the process of the "Uruma Crustal Movement" (KIZAKI and TAKAYASU, 1976). (S) The last stage of the "Shimajiri Sea". (R) The stage of the "Ryukyu Coral Sea". (T) Post-"Ryukyu Coral Sea" stage.

ghout Ryukyu Islands, . Therefore, as the Quaternary tectonic movement, the "Uruma Crustal Movement" has a significant position in the establishment of the Ryukyu arc.

C. Outline of the Quaternary Geohistory of the Ryukyu Islands

In the foregoing chapters, the writer has come to conclude that the Ryukyu Group, main part of the "Ryukyu Limestone", was the product of the tectonism during Early to early Middle Pleistocene, and not of eustatic movement alone. From this viewpoint, he tries to make an outline of the Quaternary geohistory of the Ryukyu Islands hereinafter. For convenience, it will be mentioned in following stages successively.

(I) The stage prior to the Ryukyu Group sedimentation, or the last stage of the "Shimajiri Sea" (Earliest Pleistocene).

(II) The "Ryukyu Coral Sea" stage (Early-early Middle Pleistocene)

(II/III) The maximum stage of the "Uruma Crustal Movement" (middle Middle Pleistocene)

(III) The Minatogawa stage (late Middle Pleistocene-Late Pleistocene)

(IV) The Ryukyu Islands stage (Late Pleistocene-Holocene)

(I) *The last stage of the "Shimajiri Sea"*

As a result of depth decrease of the Shimajiri Sea, calcareous sands deposited and

the Chinen Sandstone was formed. Accompanied with it, vast land areas emerged and extended near and along the present position of the Ryukyu Islands as the hinterland for successive sedimentation. Probably deer of *Metacervulus* migrated into the Ryukyu Islands area from the continental area through land bridge of East China Sea. It is probable that Honshu and its adjacent islands had been already separated from the Ryukyu Islands, and yet the latter might be without connection to Taiwan, because those fossil deer have not been reported from Honshu and Taiwan.

(II) *The "Ryukyu Coral Sea" stage*

It is the stage in which transgression initiated the deposition of the Ryukyu Group and completed its accumulation. This stage is subdivided further into the early and the late substages.

The early substage is represented by the sedimentation of the Lower Formation of the Ryukyu Group. At first, a large quantity of terrigenous materials flowed into the marginal sea from the land area of hinterland which still remained widely nearby. Consequently, the resultant decreasing of temperature, salinity, transparency, etc. of sea water might spoil the activity of reef-building organisms. Nevertheless, following the depression of basin floor oceanic conditions were introduced to the Ryukyu Islands area. Thus, some parts of the sea area might promote favourable conditions for the coral reef building. But some temporary pause of basin depression brought about suspension or relative drop of the sea level, and thus, the sedimentation of the Lower Formation of the Ryukyu Group ceased.

The late substage is the sedimentation of the Upper Formation of the Ryukyu Group. As the sea level was rising again rapidly, the sea covered the land area more widely and the depth deepened for a while. After that, the depth of the sea decreased gradually, and at last the coral reef building became more active than the previous time. Alongside of this, the tectonic movements such as the Nakagusuku Dome forming might control or influence the sedimentary facies variations. Early in this substage, archaic elephant or primitive "Mammuthus", "Archidiscodon", existed in the Ryukyu Islands area, and these elephants seem to have close relationships to the fossil elephant of the Cho-chen fauna of Taiwan of that time. Therefore, it is probable that the transient land connection between Taiwan and the Ryukyu permitted elephant migration.

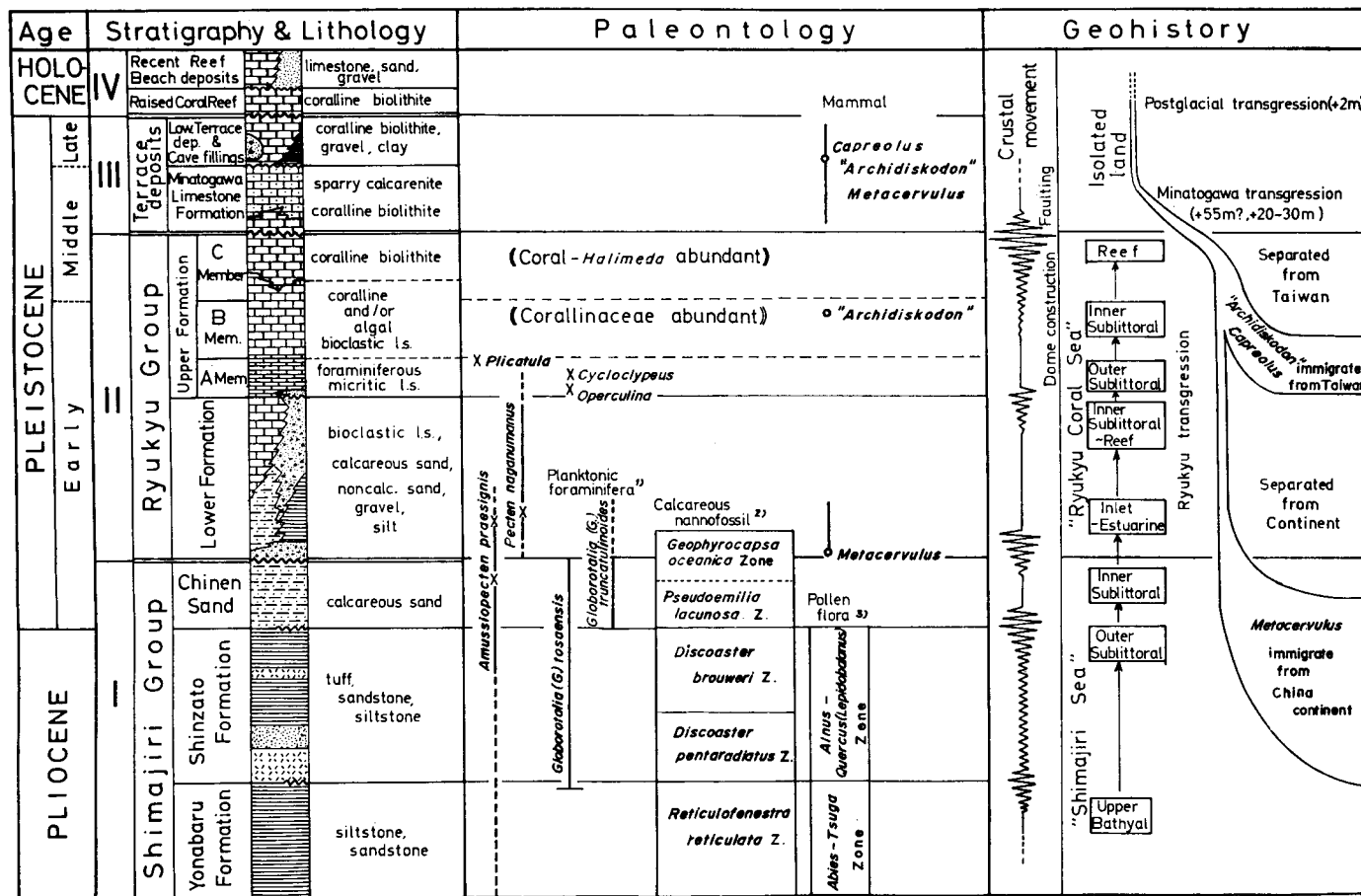
(II/III) *The maximum stage of the "Uruma Crustal Movement"*

It was the stage of destruction of the Nakagusuku Dome and dislocation of the Ryukyu Group. Thus, many tilting blocks were formed. Isolation of the Ryukyu Islands were completed, because continental land mammals of the Middle Pleistocene Chou-k'outien fauna and the Late Pleistocene Huangt'u fauna, which were present in Taiwan in one hand and Honshu area on the other hand, are not known from the Ryukyu Islands.

(III) *The Minatogawa stage*

Since this stage, it seems that the influence of the eustatic sea level changes surpass

Table 6. Summarized chart of the geohistory during the late Neogene and the Quaternary periods of the Ryukyu Islands



1) Natori et al. (1972), Ibaraki and Tsuchi (1975) ; 2) Nishida (1973) ; 3) Nishida and Itokazu (1976)

that of tectonic movements in the sedimentation. The terraces and the accessory limestones were formed around each isolated land. The latter is represented by the Minatogawa Limestone Formation, and the highest sea level of that time is inferred to be 20–30 m (or maximum about 55 m) above present sea level. Most of the deposits in caves and fissures of the "Ryukyu Limestone" might belong to this stage.

(IV) *The Ryukyu Islands stage*

Formation of the raised coral reefs at the height of about 2 m above present sea level. Deposition of the dune sand and other beach sediments. Formation of the present coral reefs.

The sequence of the geological events mentioned above is shown in Table 6.

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In carrying out fieldwork and in completing this study, I have been aided by many persons and several organizations to whom I wish to express my sincere thanks. Especially, I am grateful to Prof. T. KAMEI, Prof. K. NAKAZAWA, Associate Prof. S. ISHIDA, Associate Prof. T. SHIKI, Dr. D. SHIMIZU and Dr. T. TOKUOKA of Kyoto University for their helpful suggestions and critical readings of the manuscript, and to Prof. KIZAKI and Associate Prof. H. FURUKAWA of the University of the Ryukyus, Associate Prof. Y. OKIMURA of Hiroshima University and Dr. T. SHIBASAKI a consulting geologist for their continuing guidances and encouragements.

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Place Names

Chinen 知念	Goga, Guga 呉我	Gushikawa 具志川
Haneji-naikai 羽地内海	Hedo-misaki 辺戸岬	Henza-jima 平安座島
Ishikawa 石川	Itokazu 糸数	Itoman 糸満
Katsuren 勝連	Kouri-jima 古宇利島	Kunigami 国頭
Kyan-misaki 喜屋武岬	Machinato, Makiminato 牧港	Minatogawa 港川
Motobu 本部	Naha 那覇	Nakagusuku 中城
Nakijin 今帰仁	Nakoshi 仲尾次	O-jima 奥武島
Oyakebaru 親慶原	Shimajiri 島尻	Tairagawa 平良川
Tako-yama 多幸山	Tengan 天願	Unten 運天
Urasaki 浦崎	Urasoe 浦添	Yamada-onsen 山田温泉
Yagachi-jima 屋我地島	Yomitan, Yontan 読谷	Zakimi 座喜味

Explanation of Plate 14

- Fig. 1. Cuesta topography formed by tilting blocks, western part of Southern Okinawa.
- Fig. 2. Well stratified clastic limestone facies of the Lower Formation of the Ryukyu Group bent by faulting, near Minatogawa, central part of Southern Okinawa.
- Fig. 3. Coralline biolithite facies of the C Member of the Upper Formation of the Ryukyu Group, near Yamagawa, Motobu Town, western part of Motobu Peninsula.
- Fig. 4. *Operculina* limestones of the A Member of the Upper Formation of the Ryukyu Group, at Nakasone, Nakijin Village, eastern part of Motobu Peninsula.
- Fig. 5. Algal ball limestone of the B Member of the Upper Formation of the Ryukyu Group, near Itoman, western part of Southern Okinawa.
- Fig. 6. *Cycloclypeus* in the A Member of the Upper Formation of the Ryukyu Group, near Itokazu, eastern part of Southern Okinawa.

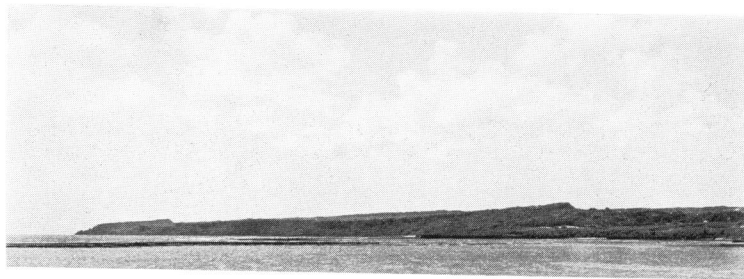
Explanation of Plate 15

- Fig. 1. Outcrop of No. M26, near Nakasone, Motobu Peninsula. Lcs; calcareous sand facies of the Lower Formation, Lcl; clastic limestone facies of the Lower Formation, UA; A Member of the Upper Formation represented by *Operculina* limestone with a dark band of terrigenous clay layer. All this section belongs to the Ryukyu Group.
- Fig. 2. Outcrop showing the relation between the Lower and the Upper Members of the Minatogawa Limestone Formation, coast of Minatogawa, central part of Southern Okinawa. C; coralline biolithite of the Lower Member, F; foraminiferal sandy limestone of the Upper Member.
- Fig. 3. Outcrop showing the regional unconformity between the Lower and the Upper Formation of the Ryukyu Group, near Gushikawa, the neck part of Katsuren Peninsula. L; noncalcareous sand and silt of the Lower Formation, U; bioclastic limestone of the Upper Formation.
- Fig. 4. Weakly layered coralline bioclastic limestone facies of the C Member of the Upper Formation of the Ryukyu Group, in Kouri-jima, off the north coast of Motobu Peninsula.
- Fig. 5. Cross lamination in the clastic limestone facies of the Lower Formation of the Ryukyu Group, near Urasaki, Motobu Town, Motobu Peninsula.
- Fig. 6. Cross bedding in the clastic limestone facies of the Lower Formation of the Ryukyu Group, near Tairagawa, Gushikawa City, Central Okinawa.

Explanation of Plate 16

- Fig. 1. Foraminiferal and algal biosparudite, the Upper Member of the Minatogawa Limestone Formation. Co; coral, Al; coralline algae (Corallinaceae), Cl; *Calcarina*, Am; *Amphistegina*, ic; intraclast, RG; grain of the Ryukyu Group, probably A Member as *Operculina* micrite. Loc., Minatogawa, central part of the Southern Okinawa.
- Fig. 2. *Cyclocypeus* biomicrudite, the A Member of the Upper Formation of the Ryukyu Group. Cy; *Cyclocypeus*, Bz; Bryozoa. Loc., STM-01, near Itokazu, eastern part of Southern Okinawa.
- Fig. 3. Foraminiferal and algal biosparmicrudite, the B Member of the Upper Formation of the Ryukyu Group. Al; coralline algae (Corallinaceae), Ha; *Halimeda*. Loc., MB-1, Koechi, Nakijin Village, Motobu Peninsula.
- Fig. 4. *Operculina* and *Cyclocypeus* biomicrudite, the A Member of the Upper Formation of the Ryukyu Group. Op; *Operculina*, Cy; *Cyclocypeus*. Loc., MB-2, Sakiyama, Nakijin Village, Motobu Peninsula.
- Fig. 5. Foraminiferal and algal biosparudite, the top part of the Lower Formation of the Ryukyu Group. Ec; Echinoid spine, TG; terrigenous grain, ic; intraclast, Al; coralline algae (Corallinaceae), Op; *Operculina*. Loc., same to Fig. 3.
- Fig. 6. Well sorted foraminiferal and algal biosparite, the upper middle part of the Lower Formation of the Ryukyu Group. Loc., M-50, Urasaki, Motobu Town, Motobu Peninsula.

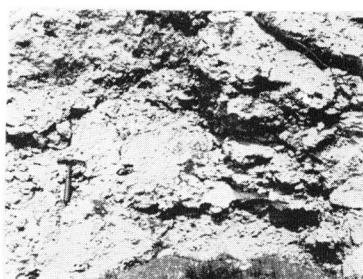
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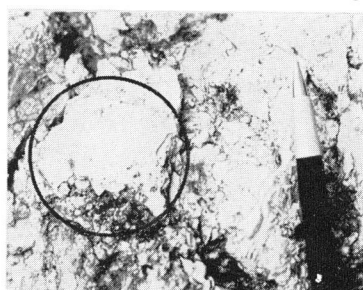
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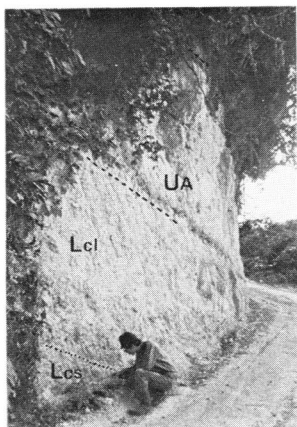


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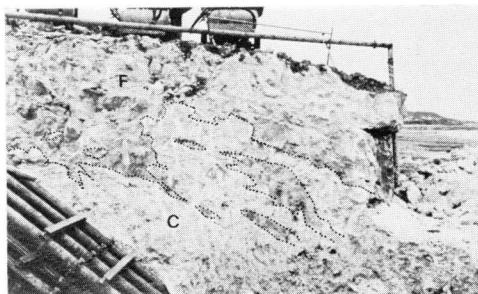


TAKAYASU: "Ryukyu Limestone" of Okinawa-jima

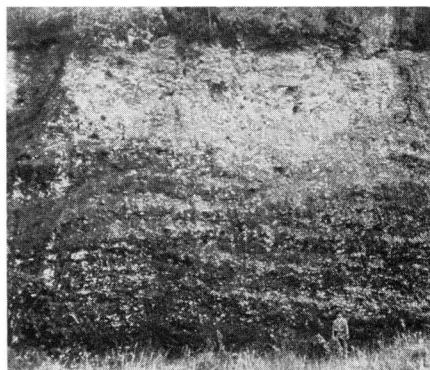
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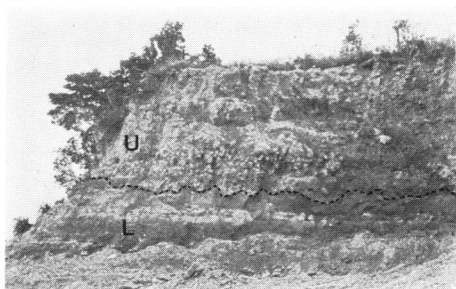
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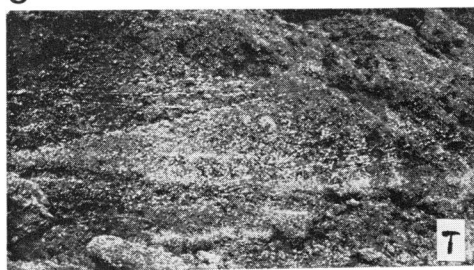
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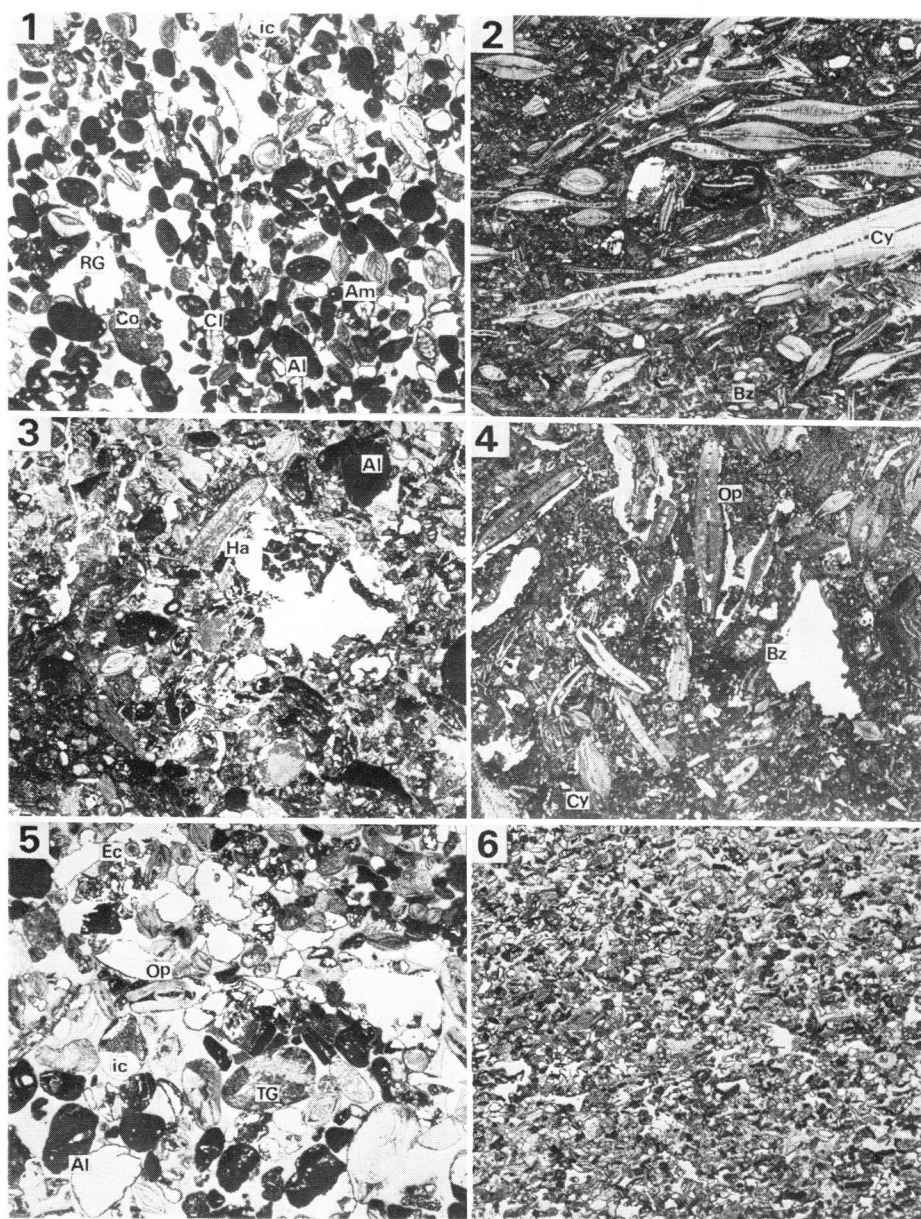


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(photo by Mr. Y. Okazaki)

5mm

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